Gravitational Lensing & Cosmology: Einstein's Unfinished Symphony

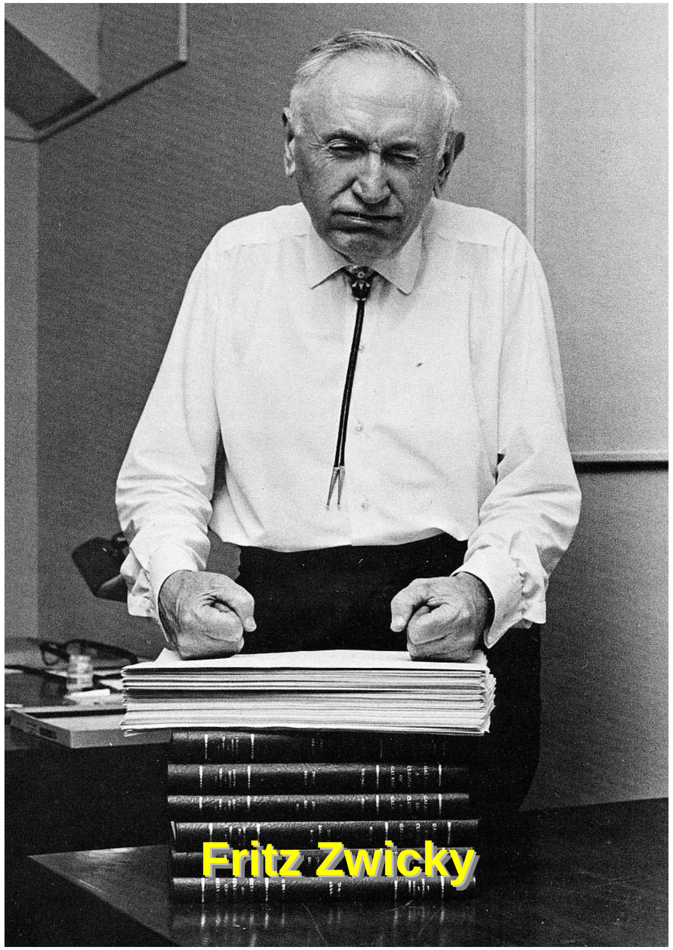
Elizabeth Spreadbury Lecture

Richard Ellis
(Oxford)

University College London **April 21st 2008**

Two rogue cosmic ingredients

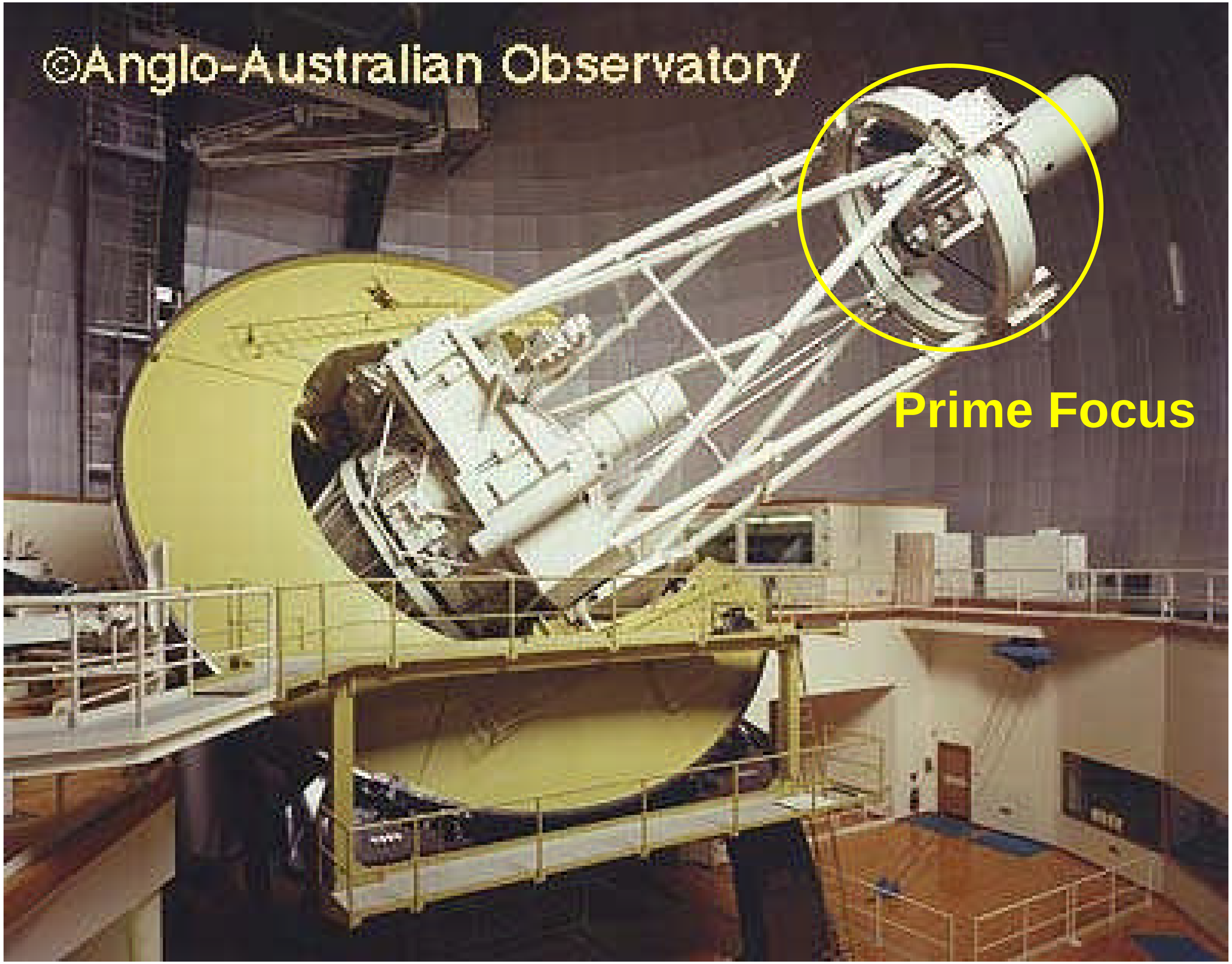
Dark Matter (1933 -)



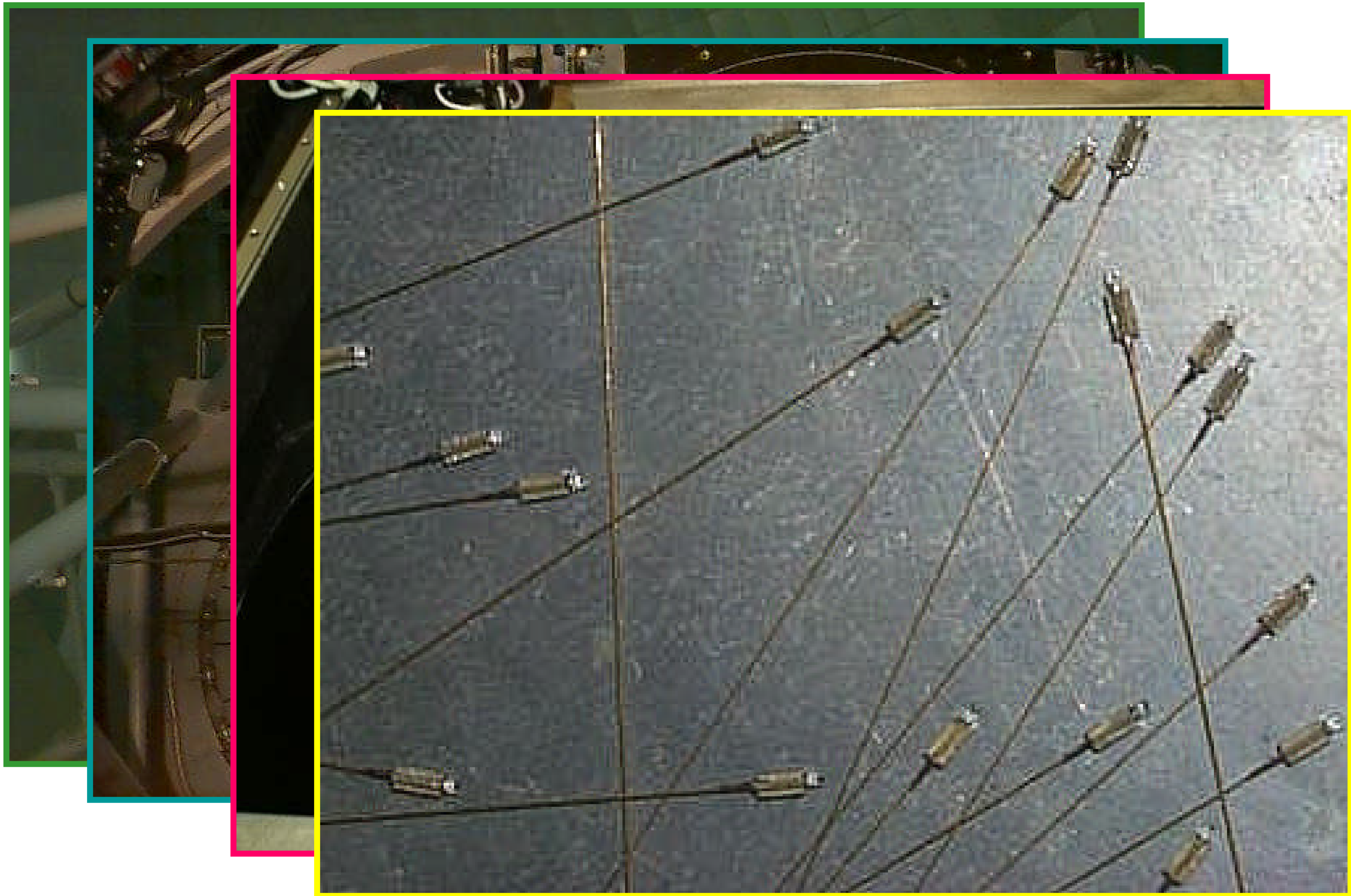
Dark Energy (1998 -)

How can we understand these observationally?

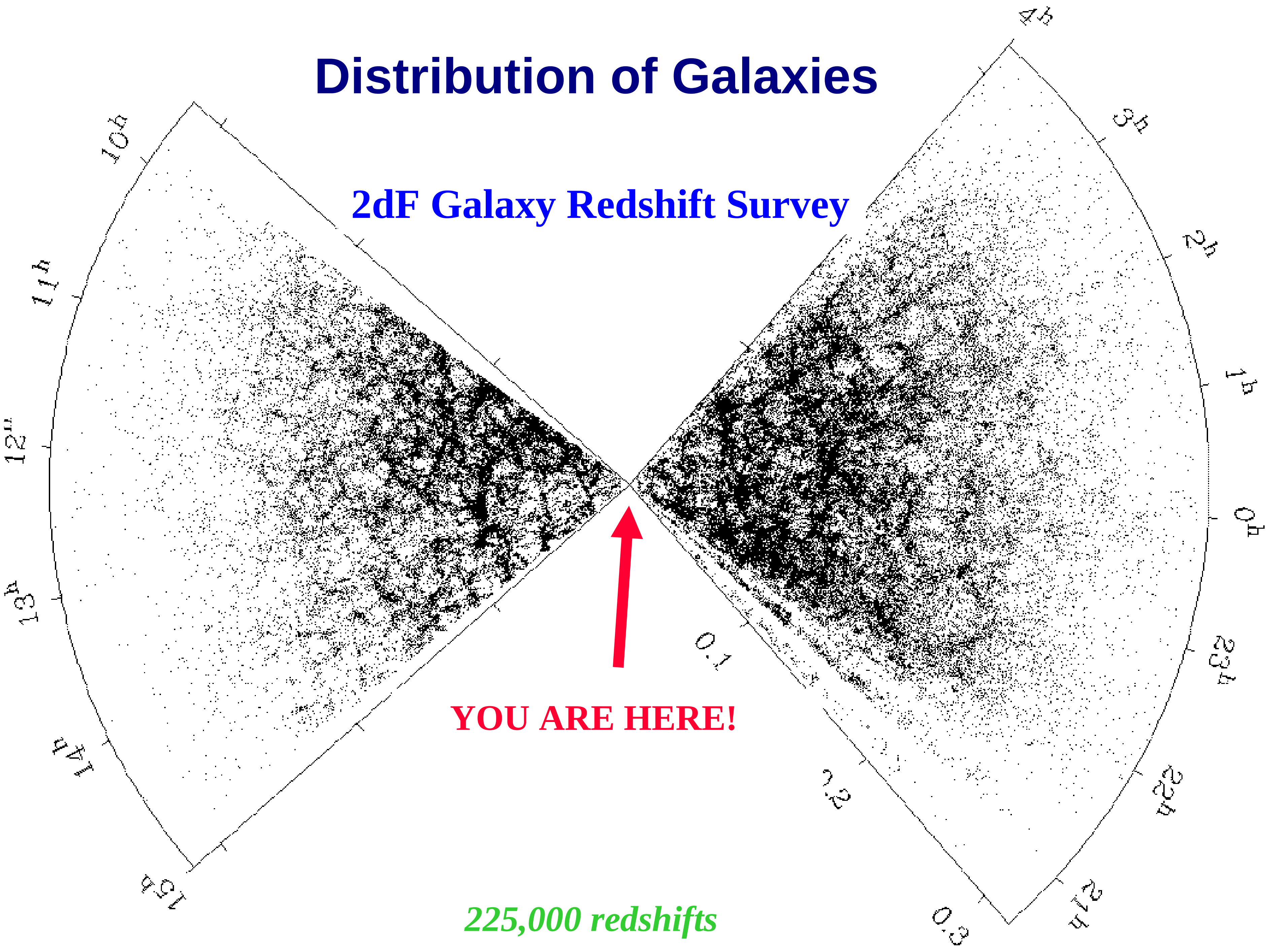
Progress in Cosmology: - I



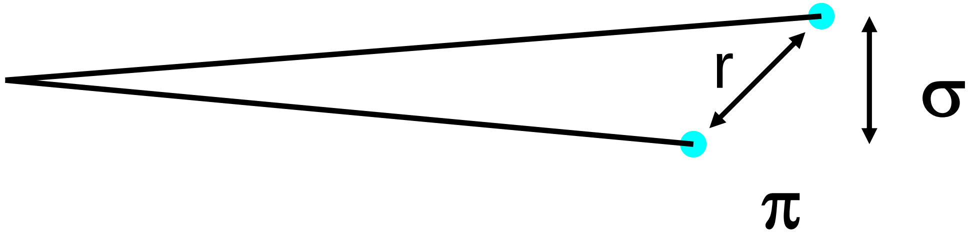
2dF on the AAT



Distribution of Galaxies



2dF redshift-space distortions



- Effect of gravitating mass quantified by a two parameter correlation function $\xi(\sigma,\pi)$

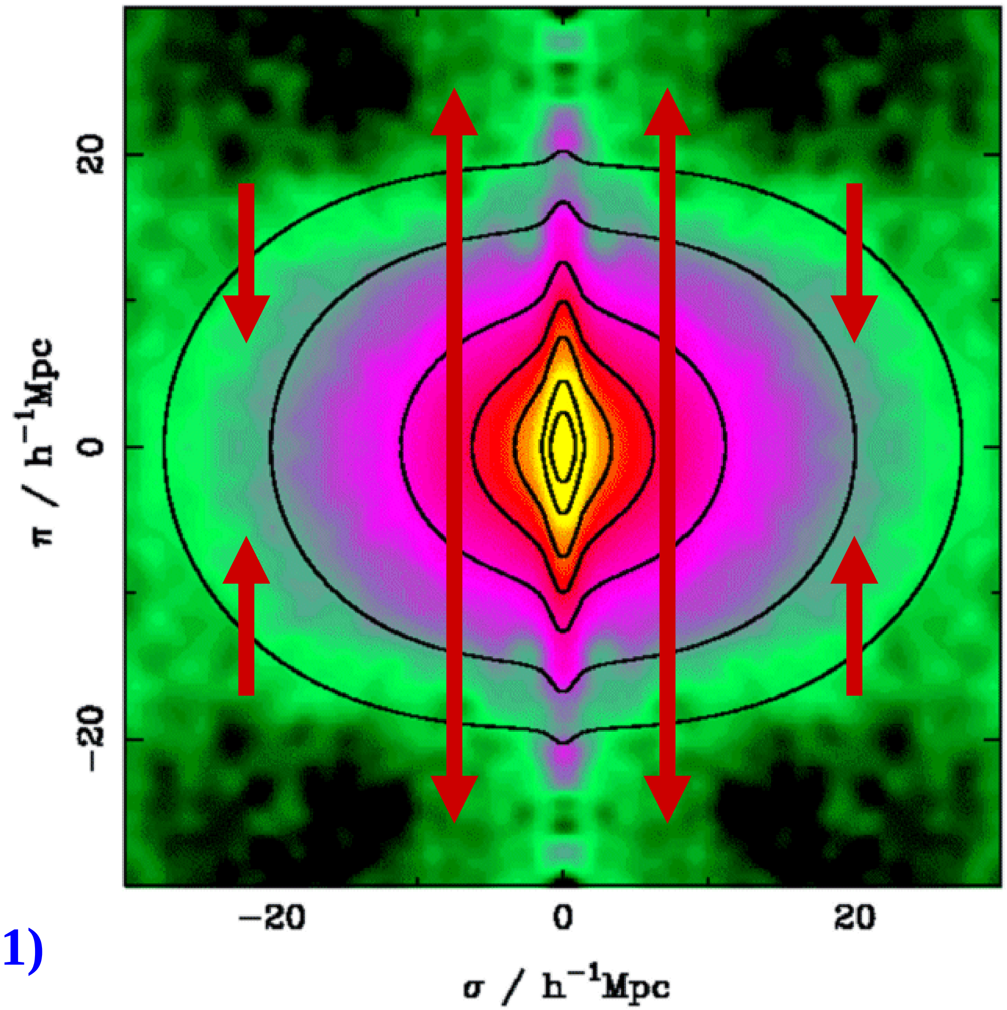
- Two effects visible:

  Small separations: ‘Finger-of-God’ elongation

  Large separations: line of sight flattening

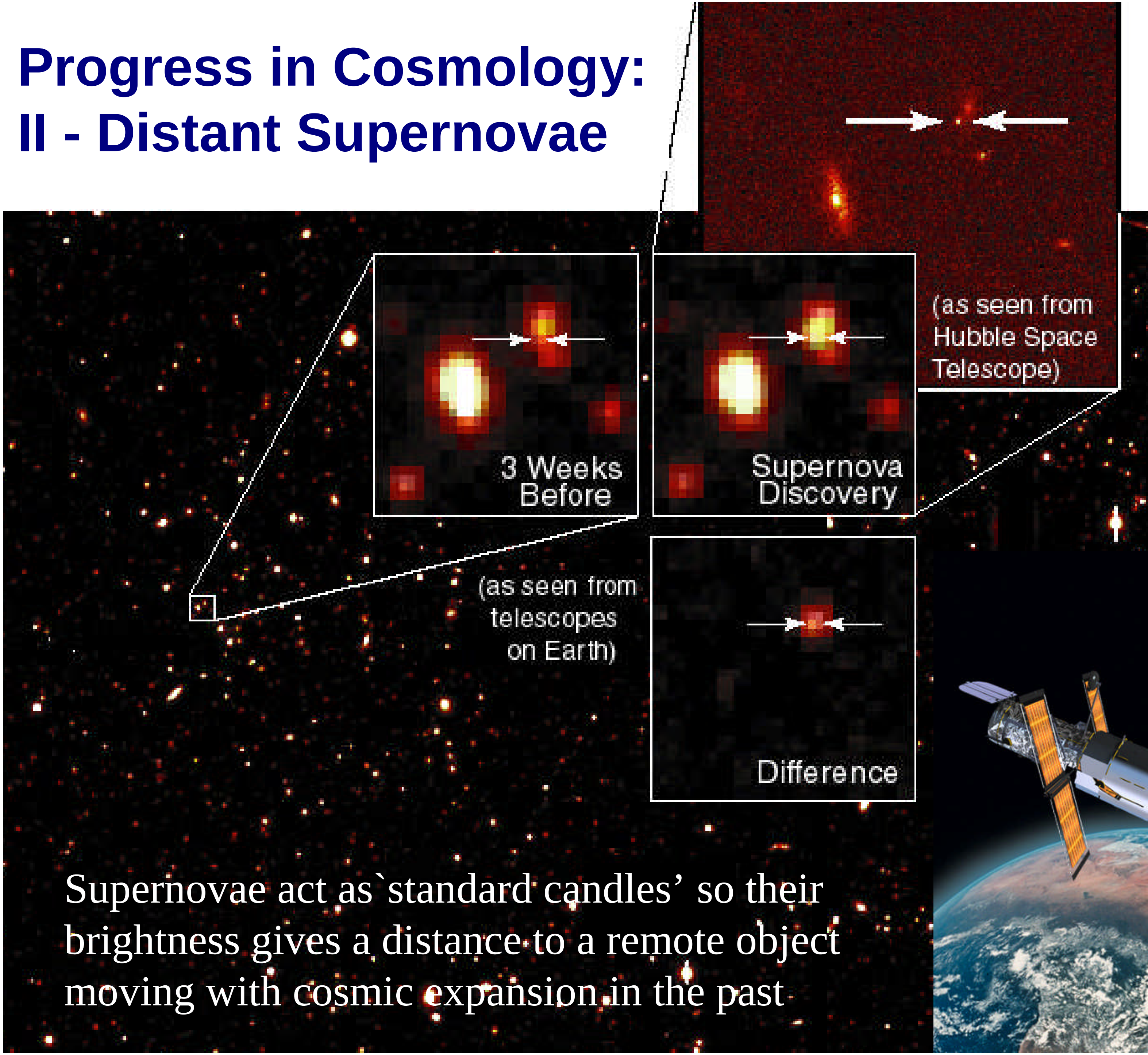
$\rightarrow \Omega = \rho / \rho_{crit} \approx 0.3$

LOW MASS DENSITY



Peacock et al, Nature, 410, 169 (2001)

Progress in Cosmology:
II - Distant Supernovae



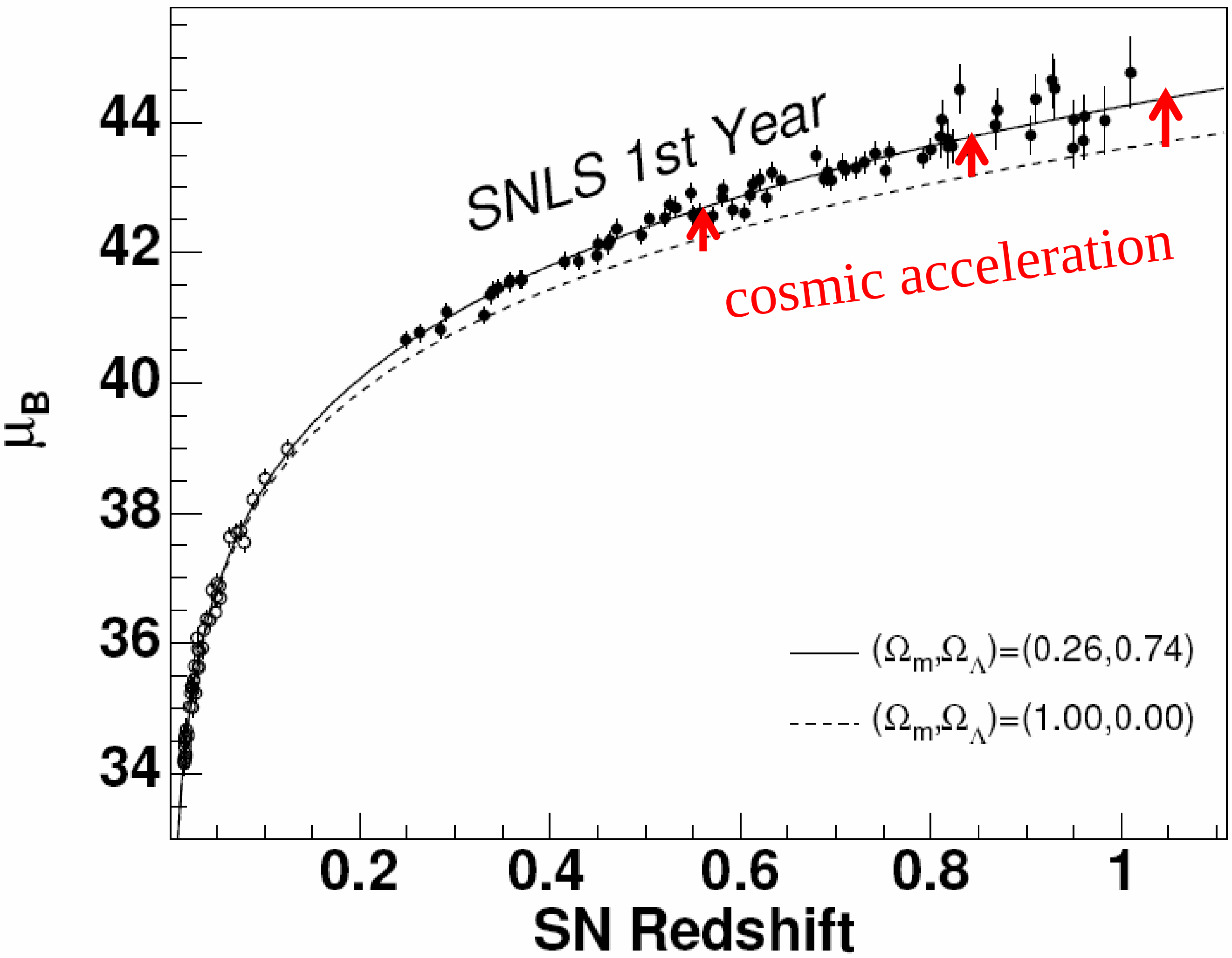
Supernovae act as`standard candles' so their brightness gives a distance to a remote object moving with cosmic expansion in the past

Measuring the Cosmic Acceleration

Astier et al A&A 447, 31 (2006)

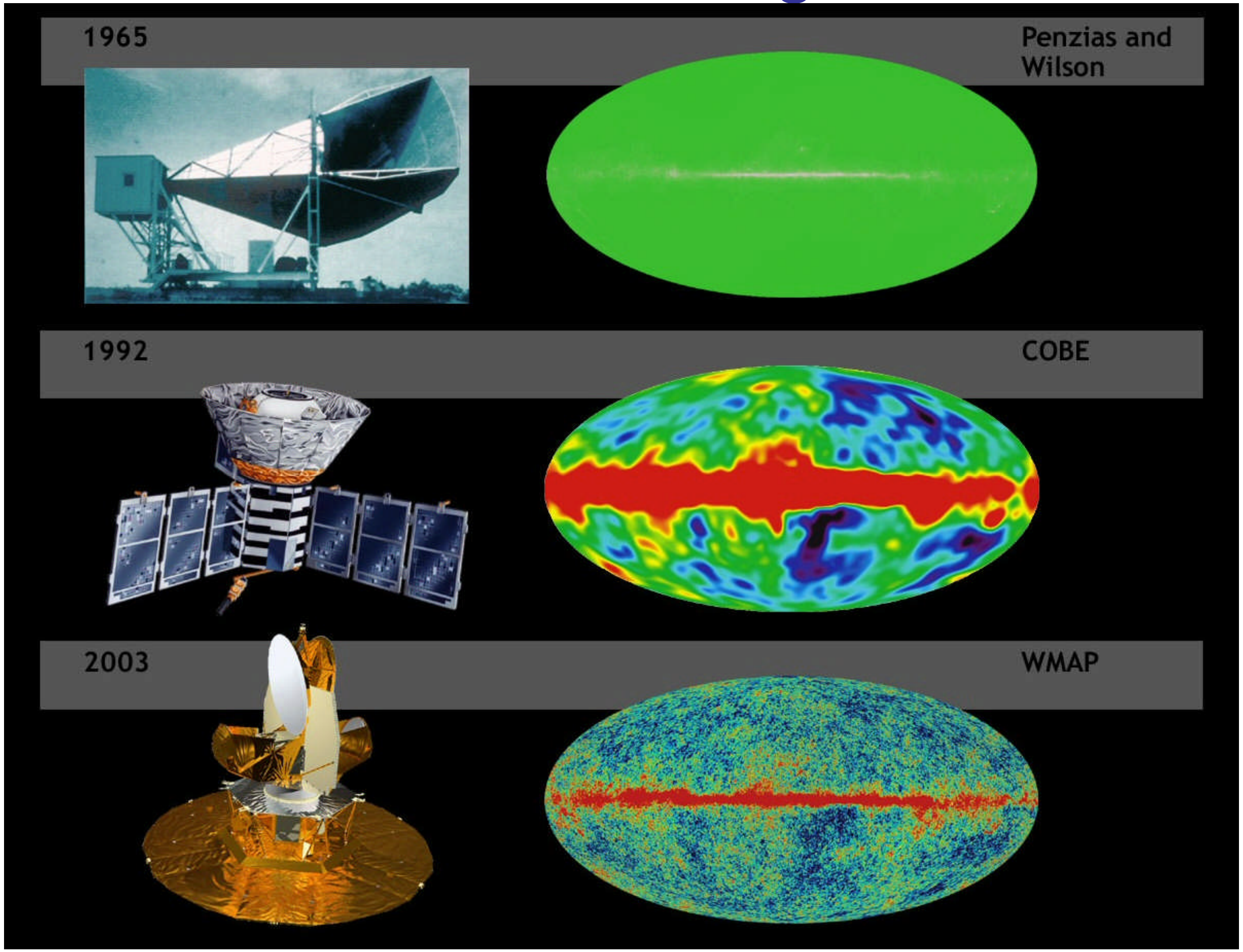
Distant SNe are fainter at a given redshift than would be the case in a matter-dominated Universe.

Introduces need for cosmic acceleration: dark energy consistent with Λ to 9%



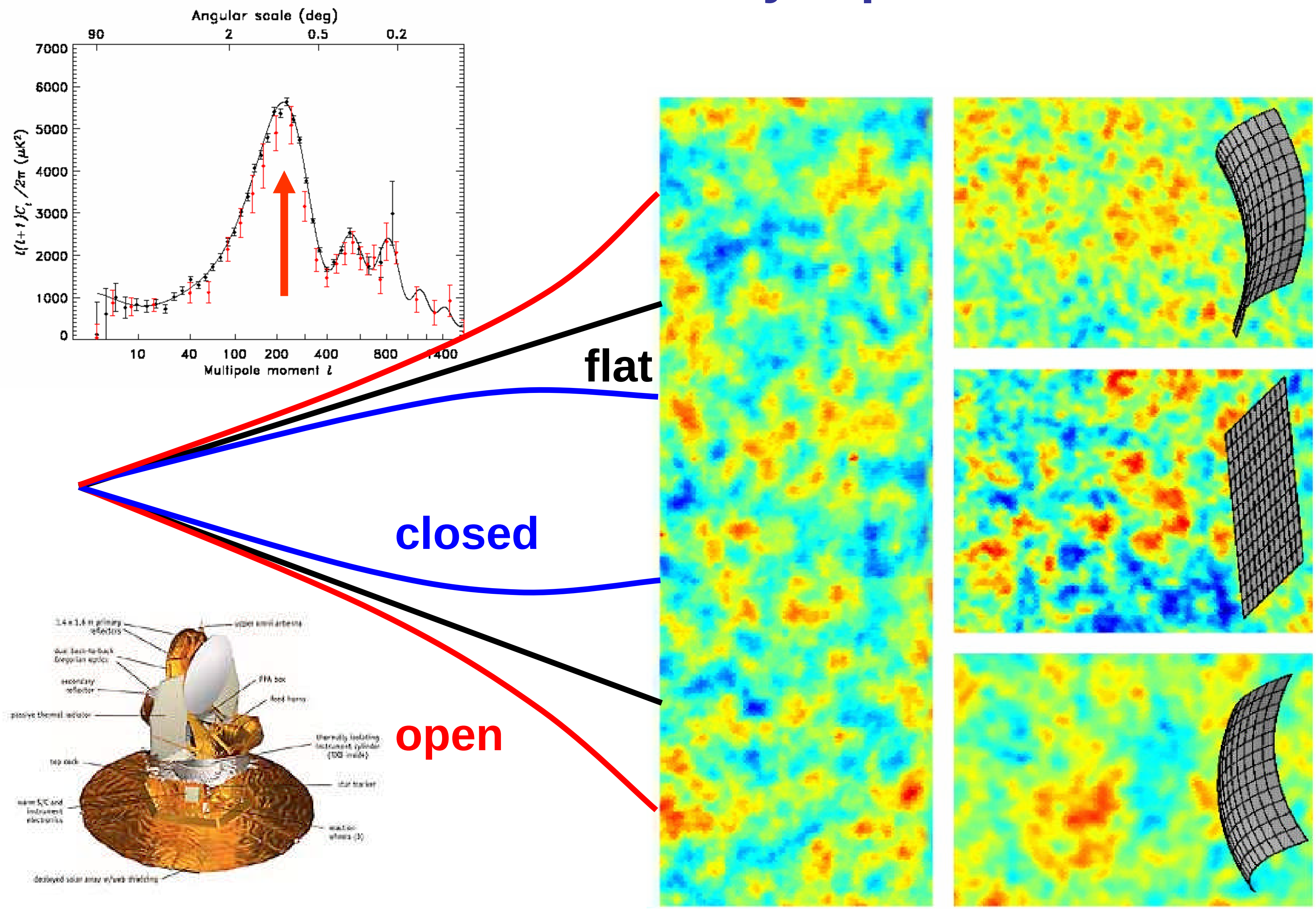
…third year results imminent: Λ to 6%!

Progress in Cosmology: III - Microwave Background



Microwave background corresponds to separation of matter & radiation at redshift $z = 1088 \pm 1$ when age = 372,000 years

Cosmic Geometry: Space is Flat!



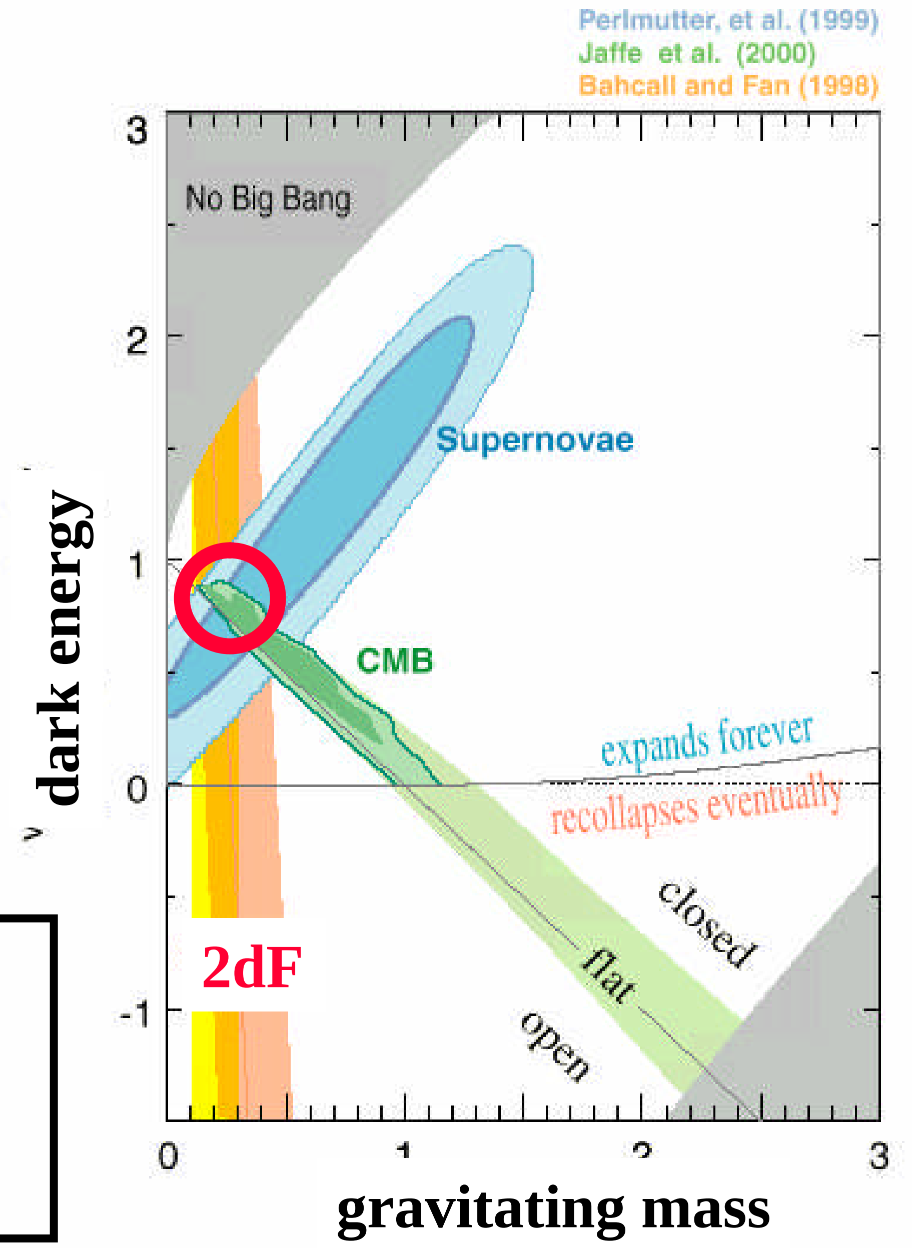
"Concordance Cosmology"

"Precision Cosmology"

- $\Omega_{DM} \approx 0.279 \pm 0.015$ (dark matter)
- $\Omega_{B} \approx 0.0462 \pm 0.001$ (baryons)
- $\Omega_{\Lambda} \approx 0.721 \pm 0.015$ (dark energy)

(Hinshaw et al 2008)

All 3 ingredients comparable in magnitude but only one component physically understood!



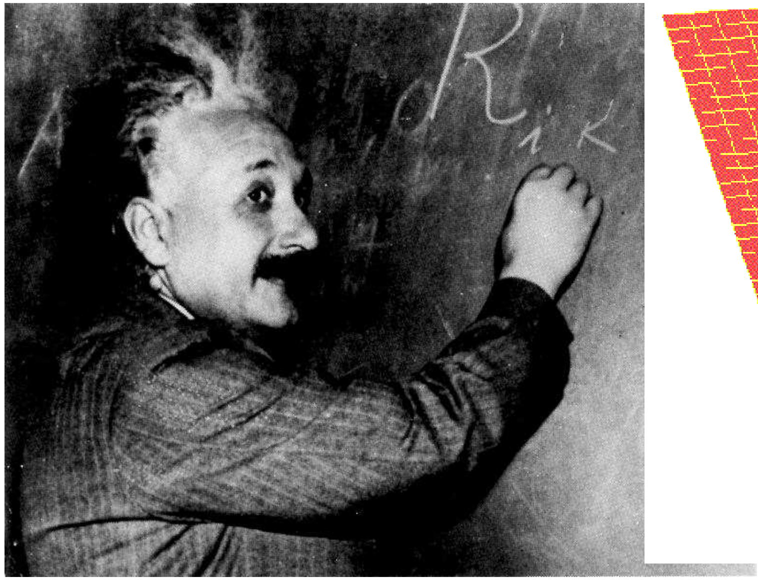
Dark Energy equation of state:

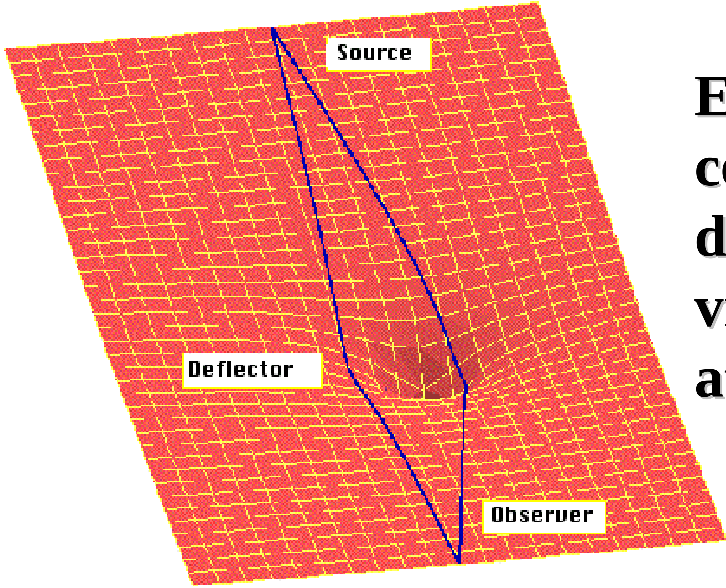
$p / \rho = w$

$w = -1$ corresponds to Λ

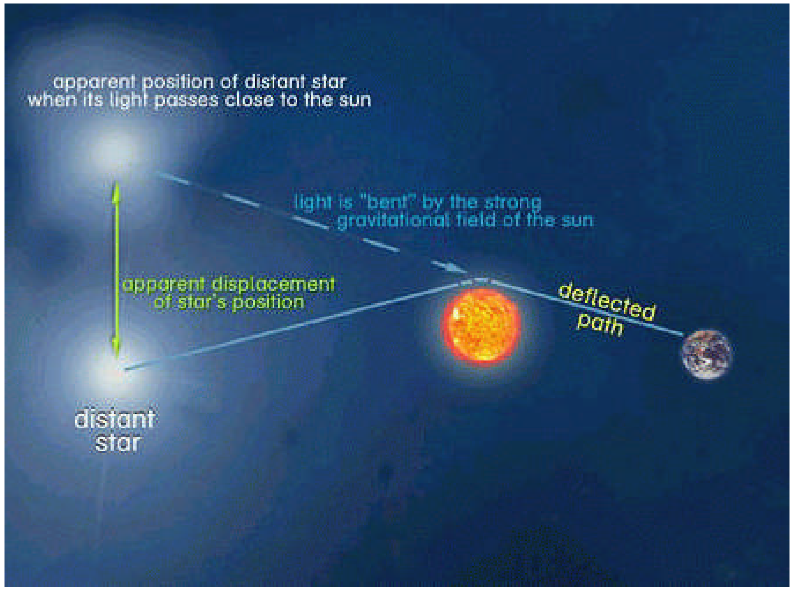
$w < 1/3$ required for acceleration

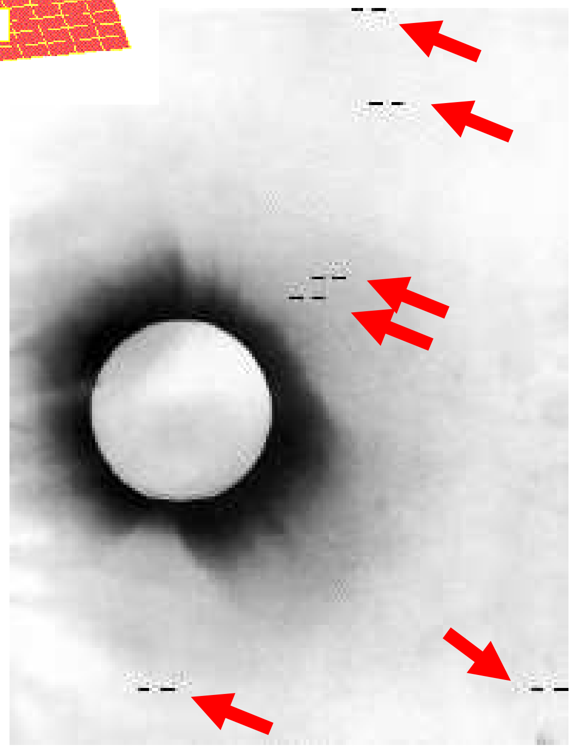
Gravitational Lensing: Curious History





Eddington (1919) confirms the sun deflects starlight via measurements at a total eclipse



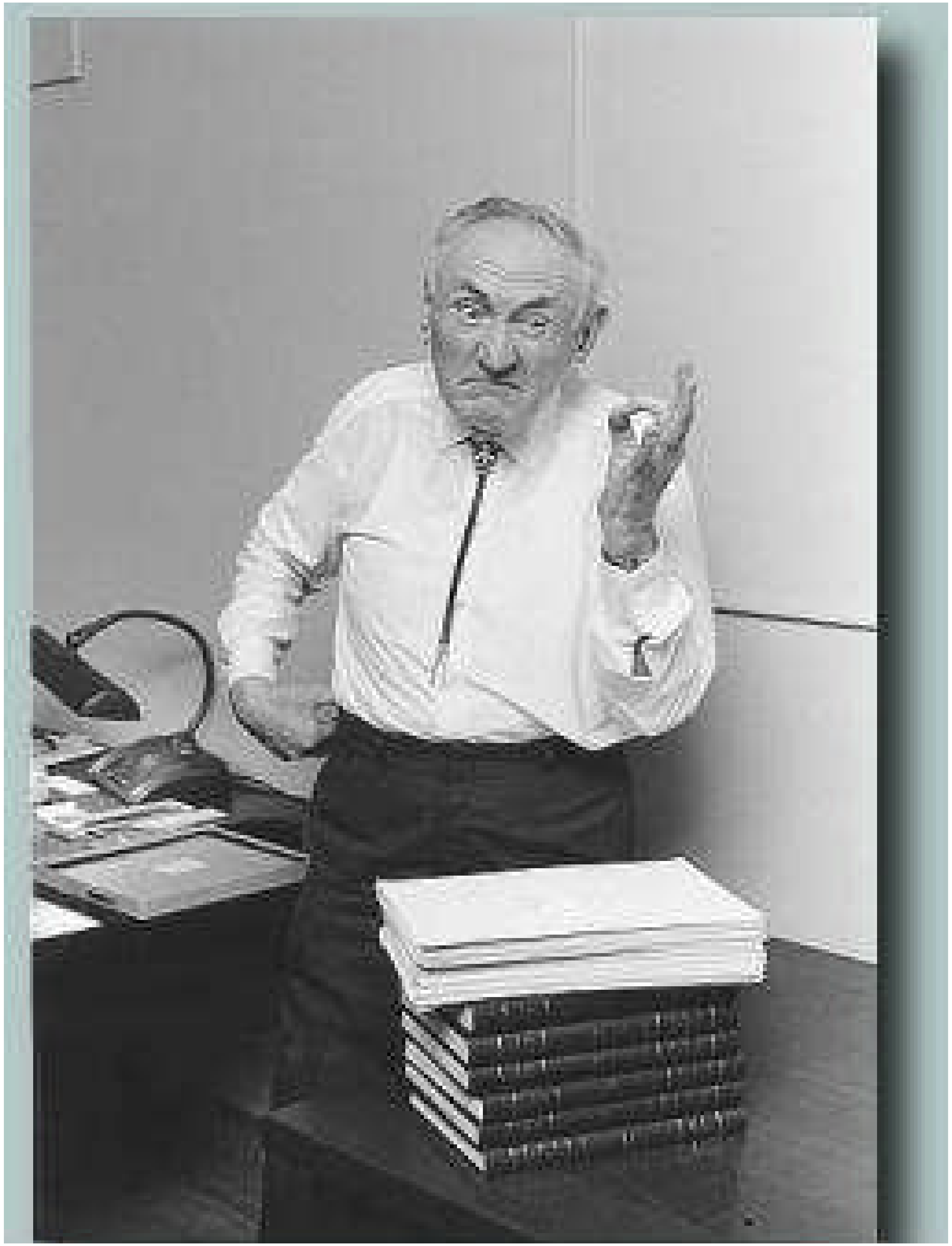


Fritz Zwicky: the irascible pioneer

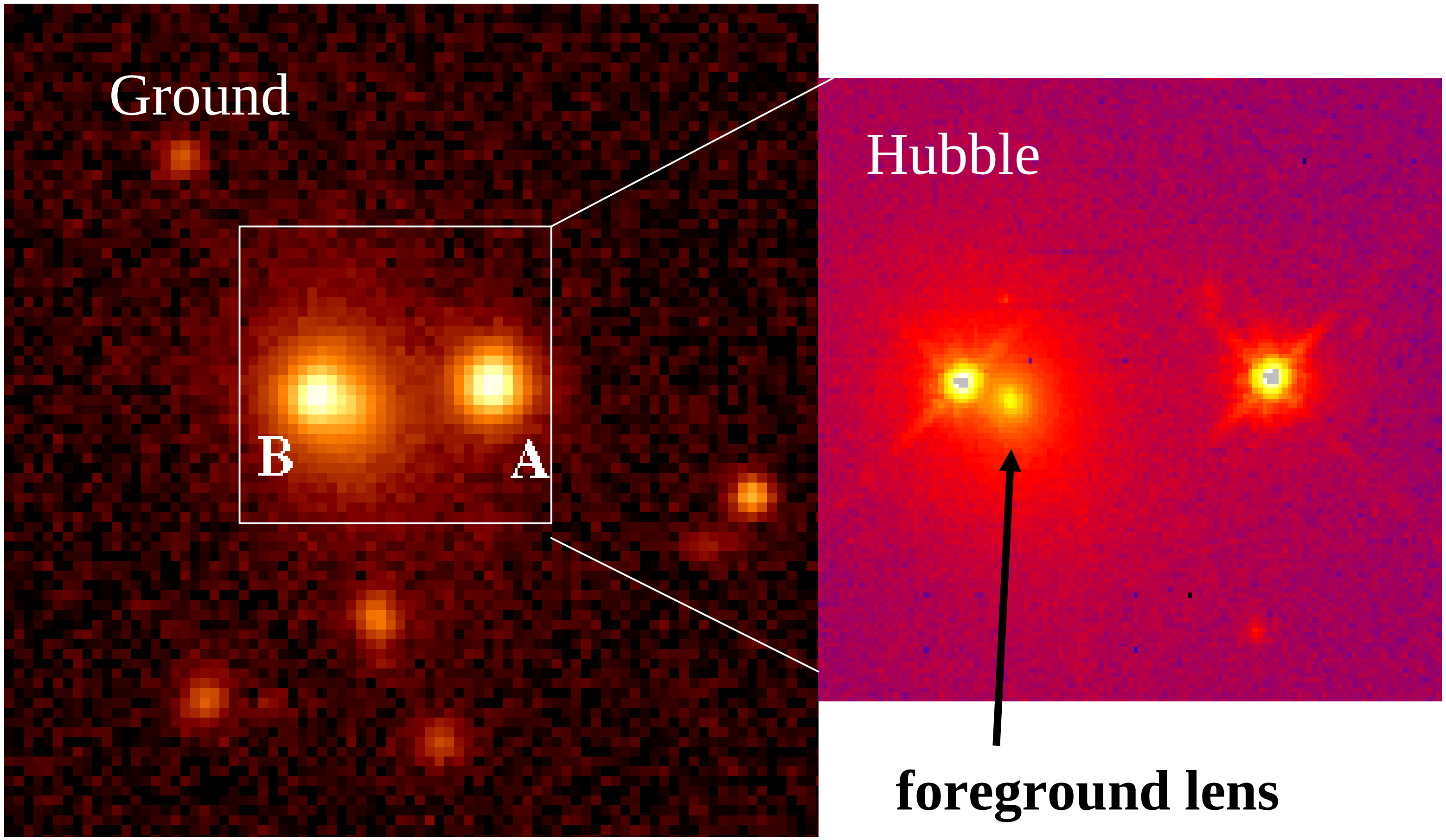
Contrary to proclamations by Einstein, Eddington and others, Zwicky (1936) predicts gravitational lensing will be invaluable in:

- tracing and measuring the amount of dark matter thought to pervade the cosmos
- magnifying distant objects

Never lived to see the renaissance..

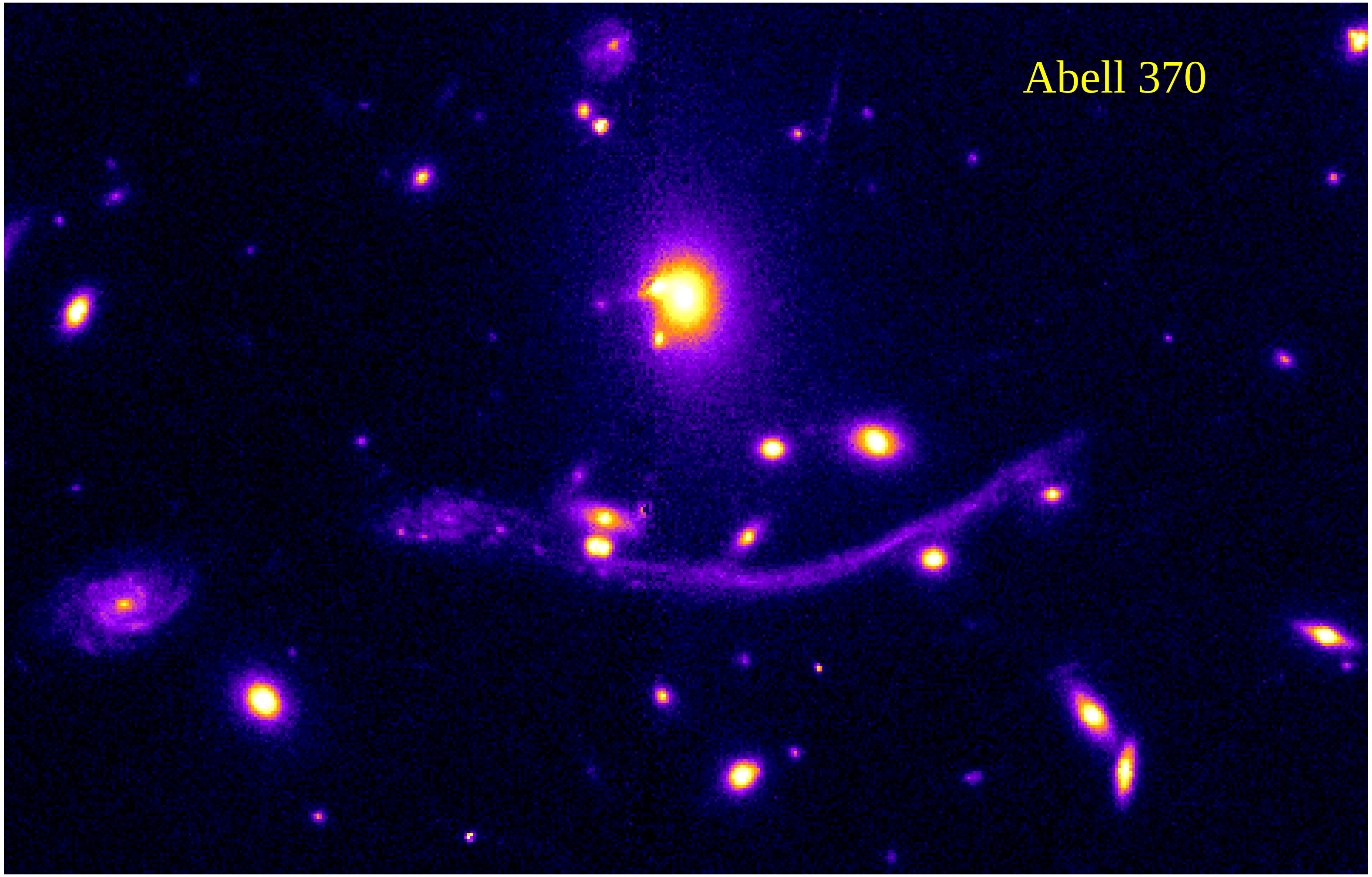


The "Double Quasar"



1979: Walsh et al show two quasars are images of a single object split by a foreground faint galaxy. The first demonstration of lensing since 1919

The First Giant Arc in a Cluster of Galaxies



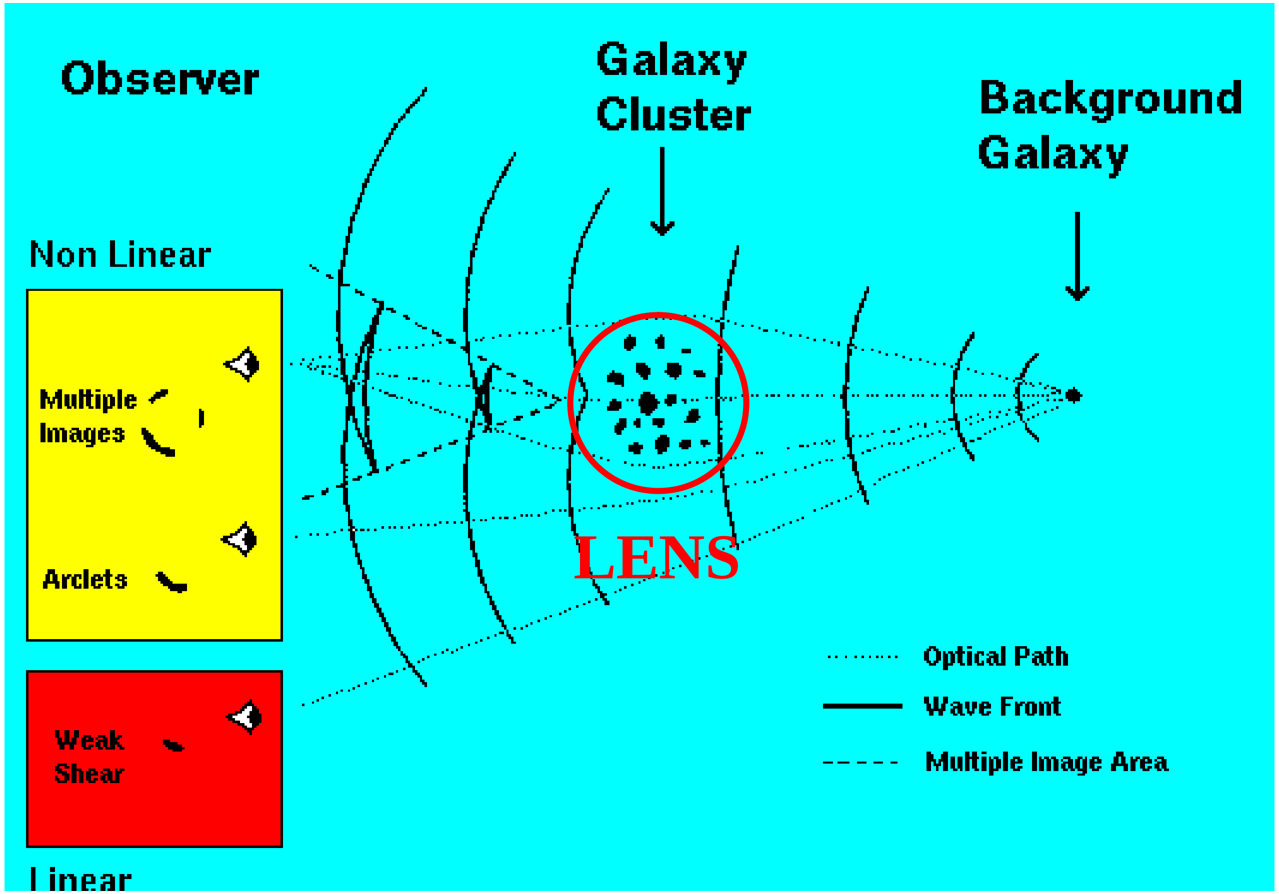
In 1987 Genevieve Soucail (Toulouse) demonstrated the arc in the galaxy cluster Abell 370 represents light of a single background galaxy distorted by the foreground cluster lens

How it works: two regimes (strong/weak)

Strong lensing (multiple images)

↓

weak distortion



What the observer sees, viewing through a lens, depends on the focusing power of the lens, the relative distances of lens and background source and the degree of alignment of both

Simulated view through transparent dark lens

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Courtesy: Lars Christensen (ESA)

Lensing Finally Comes of Age…

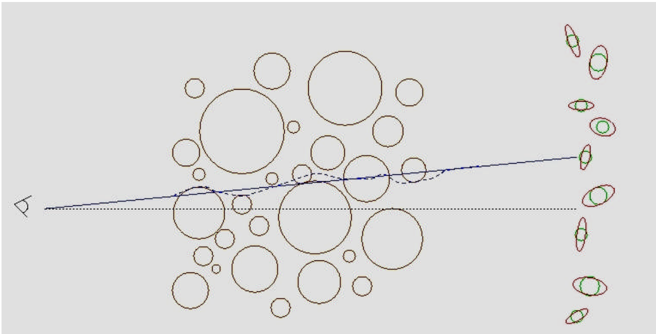
I: - Weak lensing: statistical characterization of the DM distribution in terms of mass power spectrum; its evolution provides strong constraint on *w* (independently of SNe & with less assumptions), also maps of where the DM lies!

II: - Strong lensing: multiply-imaged sources and large scale shear tests "universal" mass profile predicted in cold dark matter models; is DM non-interacting?

III: - Strong magnification: use of cluster lenses as "natural telescopes" to survey distant Universe and set first limits on abundance & formation epoch of "first light" stellar systems

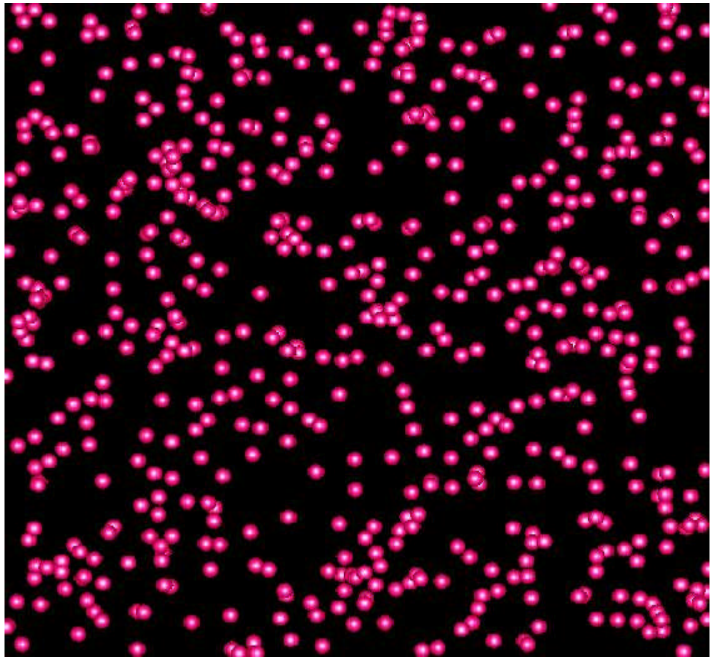
Collaborators: Richard Massey, David Sand, Dan Stark, Johan Richard (Caltech), Tommaso Treu (UCSB), Jean-Paul Kneib (Marseille)

Weak Gravitational Lensing

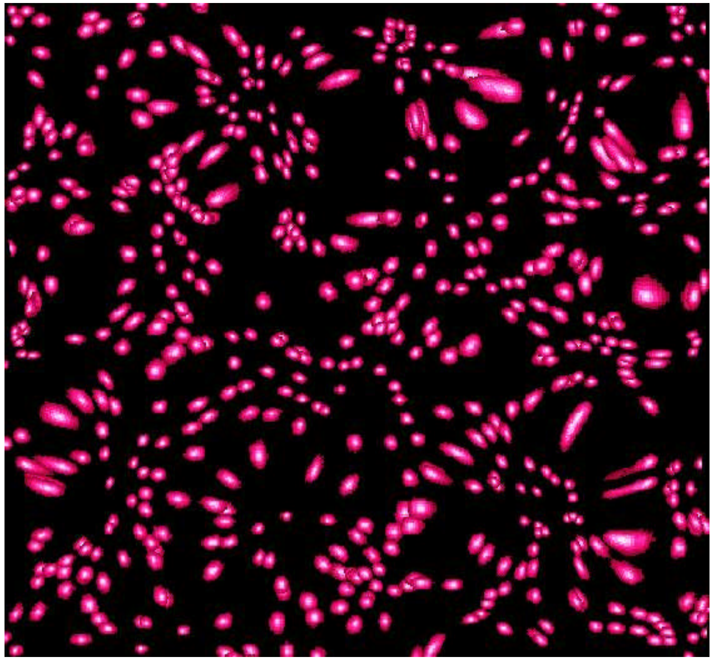


Intervening dark matter distorts the pattern of galaxy shapes on the sky:

Very weak signal - 1% distortion!

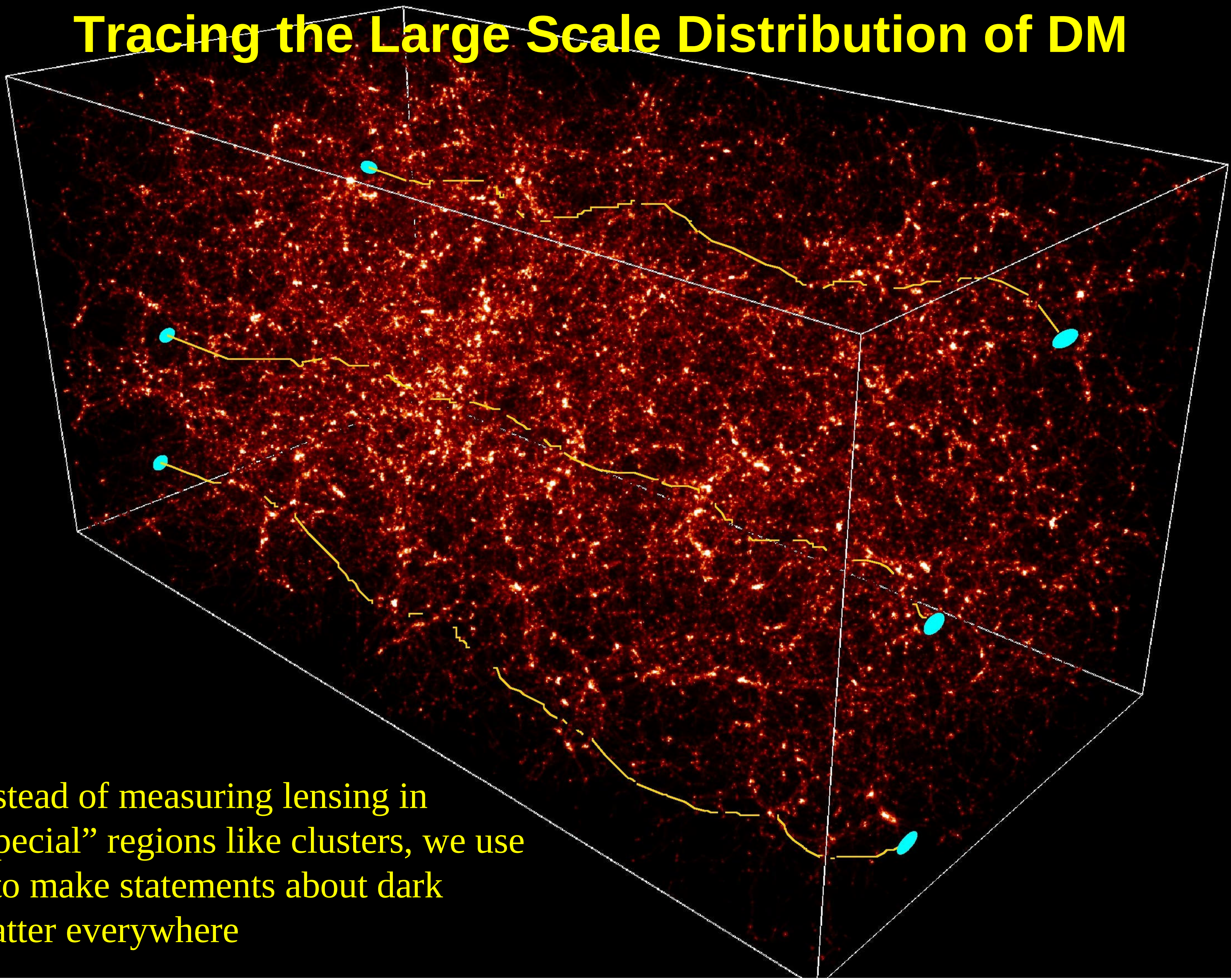


Unlensed



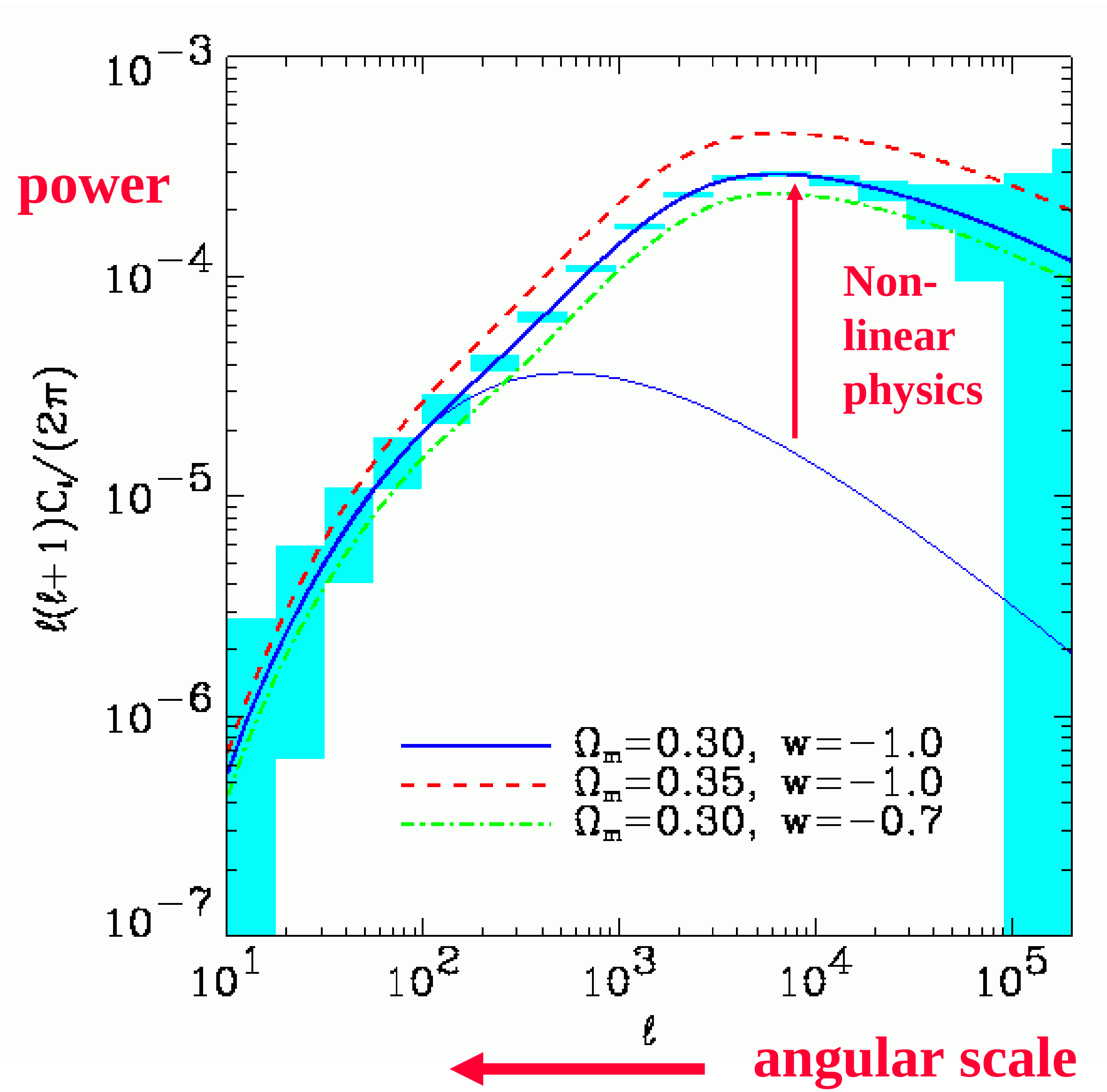
Lensed

Tracing the Large Scale Distribution of DM



Instead of measuring lensing in "special" regions like clusters, we use it to make statements about dark matter everywhere

Statistical Description of DM Distribution: Power Spectrum



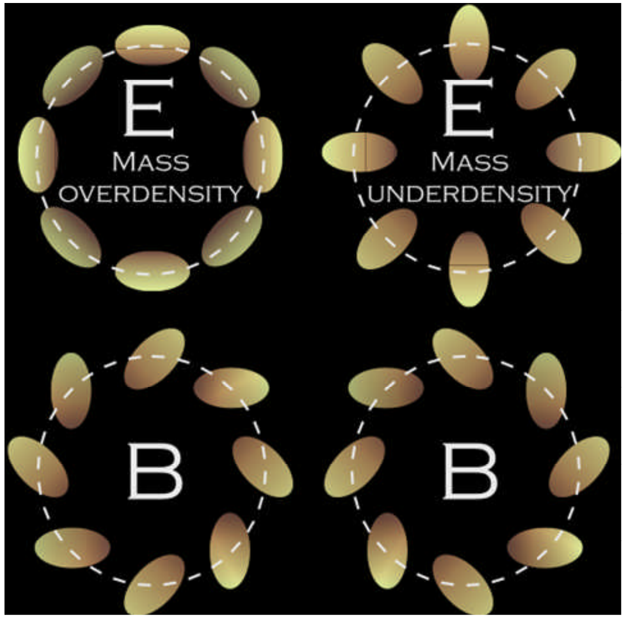
The angular DM power spectrum is analogous to that of CMB

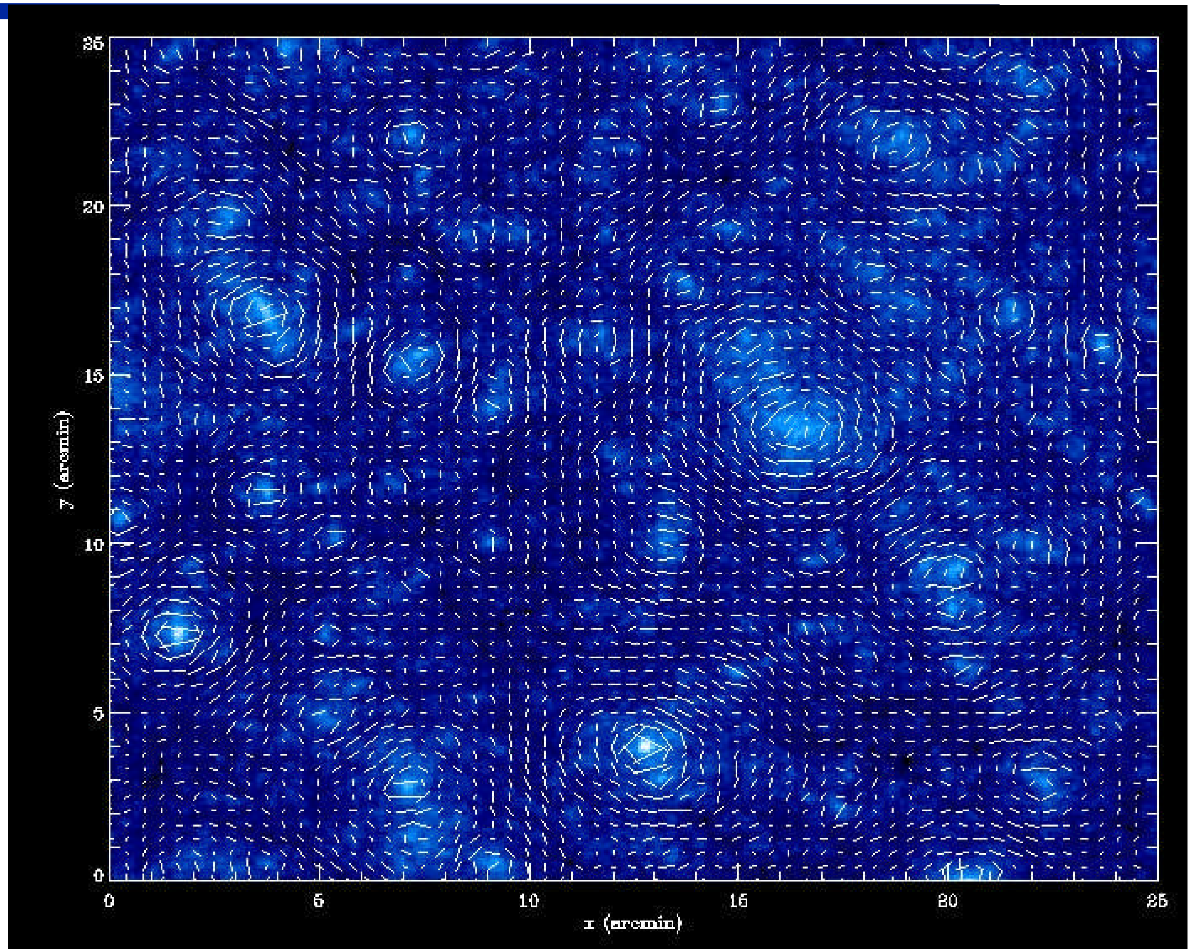
- provides direct probe of ***projected DM distribution*** free from “bias” and astrophysical assumptions

- probes complexities of non-linear regime

- constrains cosmology (modulo degeneracies between σ_8, Ω_M and ***w***)

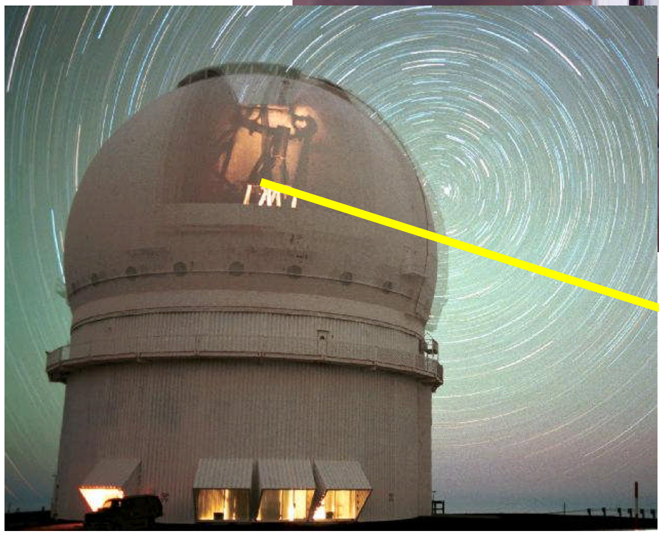
How it Works…

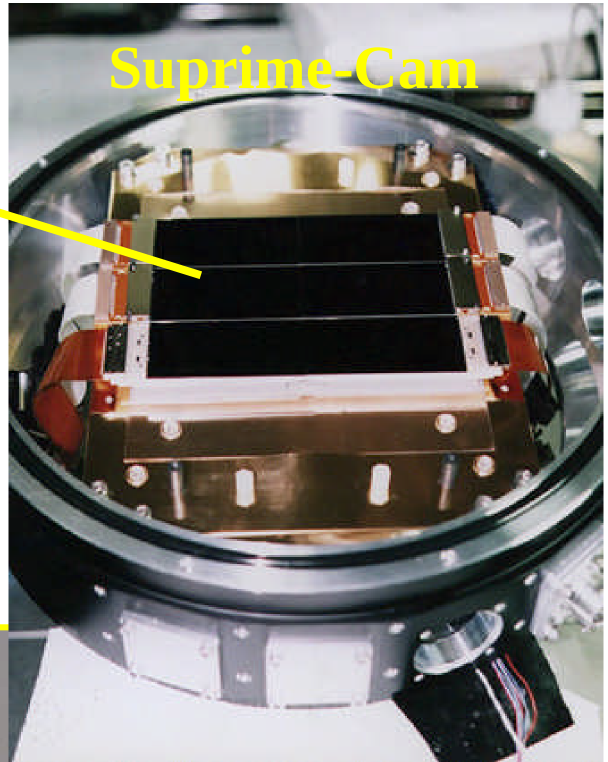


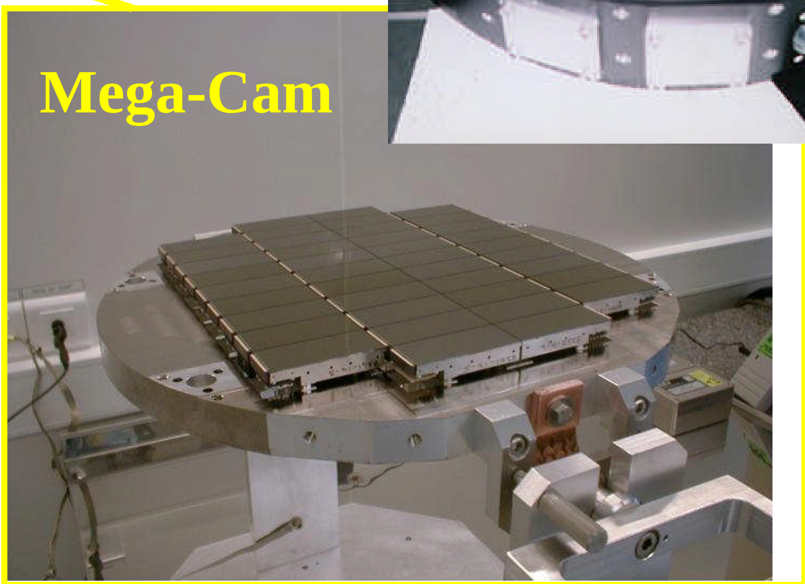


Analysis of the E-mode signal, revealed by the mean distorted shape in a given direction, can be used to infer the dark matter density along the line of sight. The B-mode, which should be zero, gives a measure of instrumental systematics

Wide Field Imaging from CFHT/Subaru





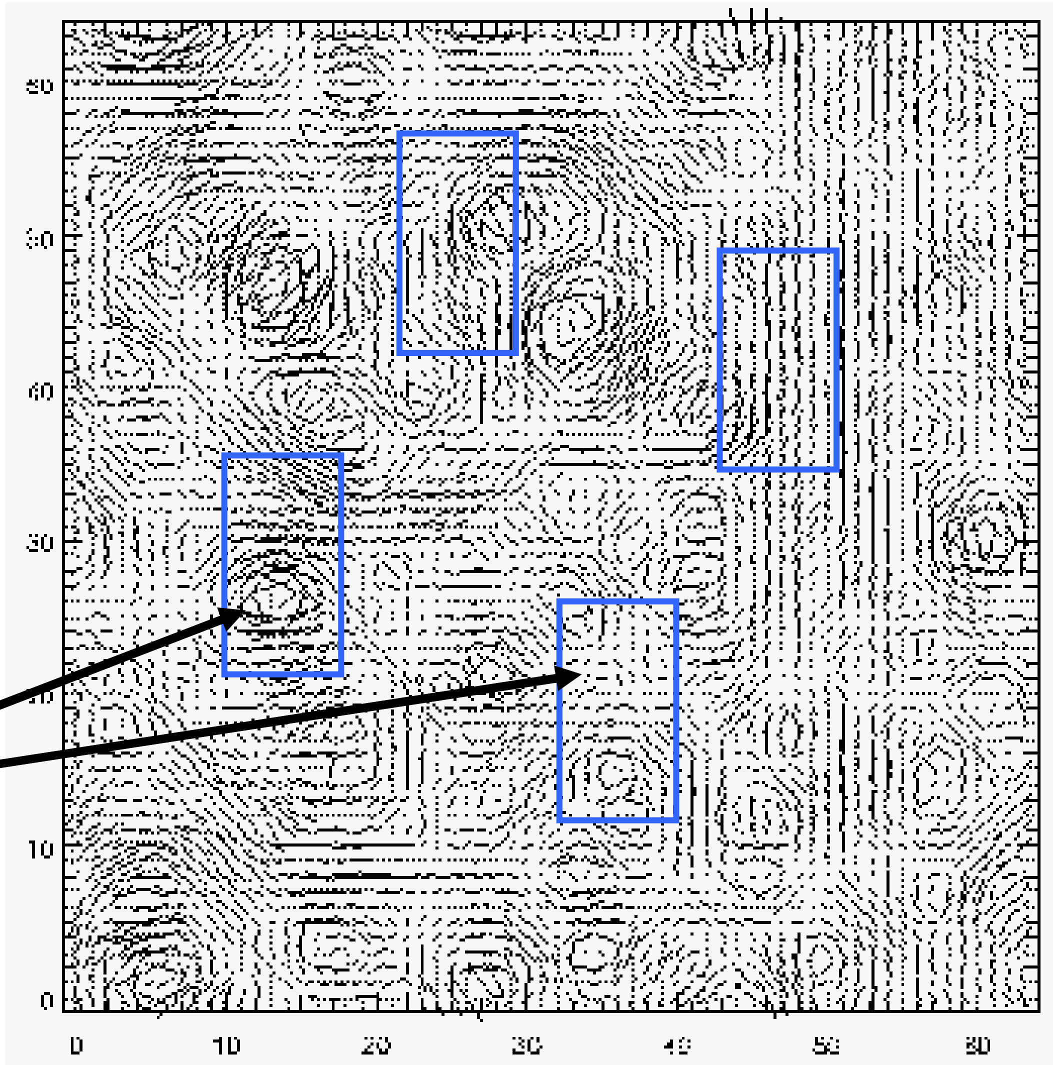


CFHT: 100deg^2 (Mellier et al)

Subaru: 30 deg^2 (Miyazaki et al)

Statistics of the DM distribution

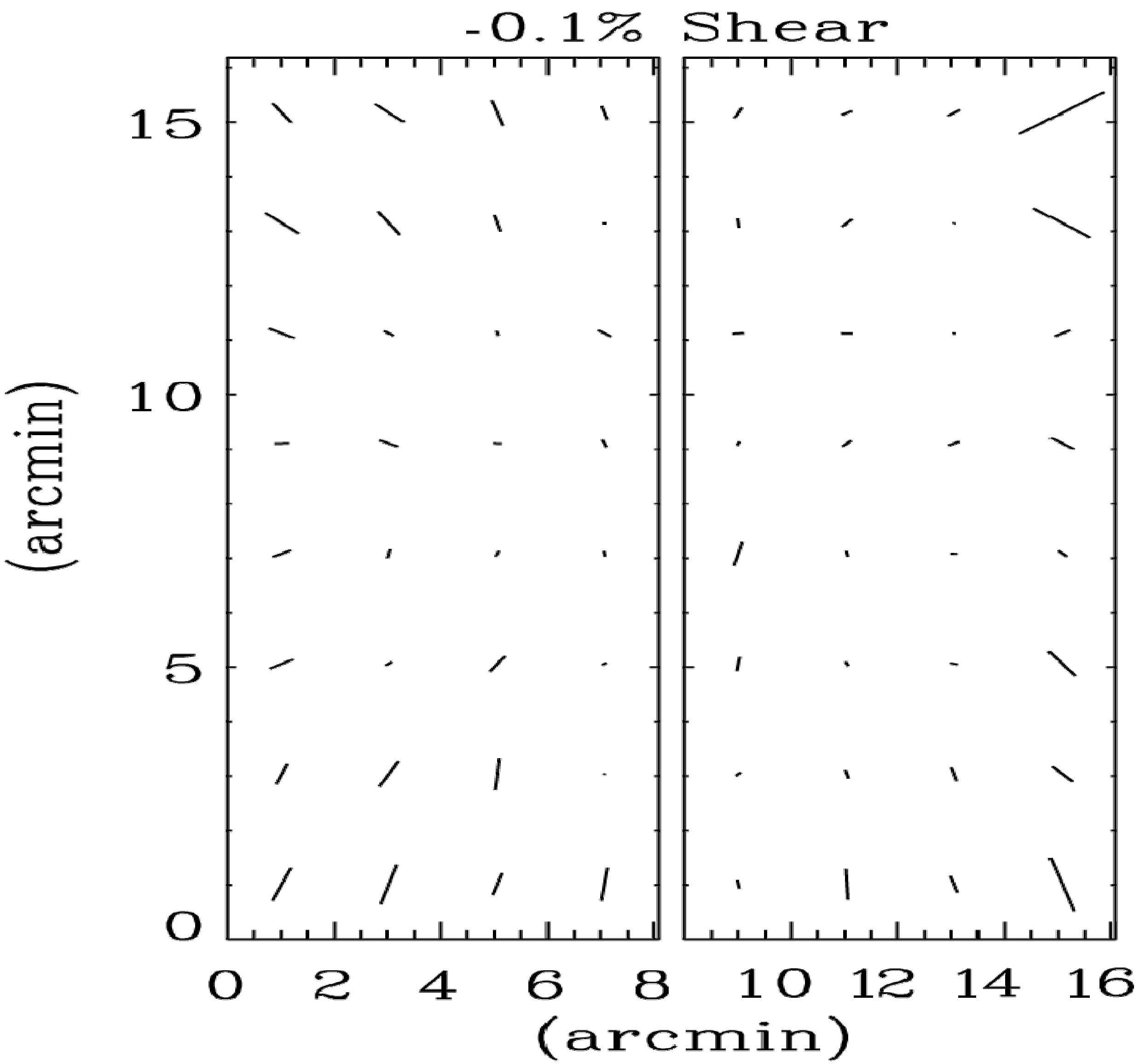
Ultimately seek to map the DM directly but first step is to accurately trace its *statistical distribution*

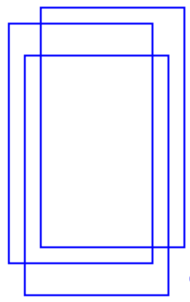


~1% shear correlation in random fields

1 sq. degree ray traced simulation of shear field

Clean physics: tough measurement!



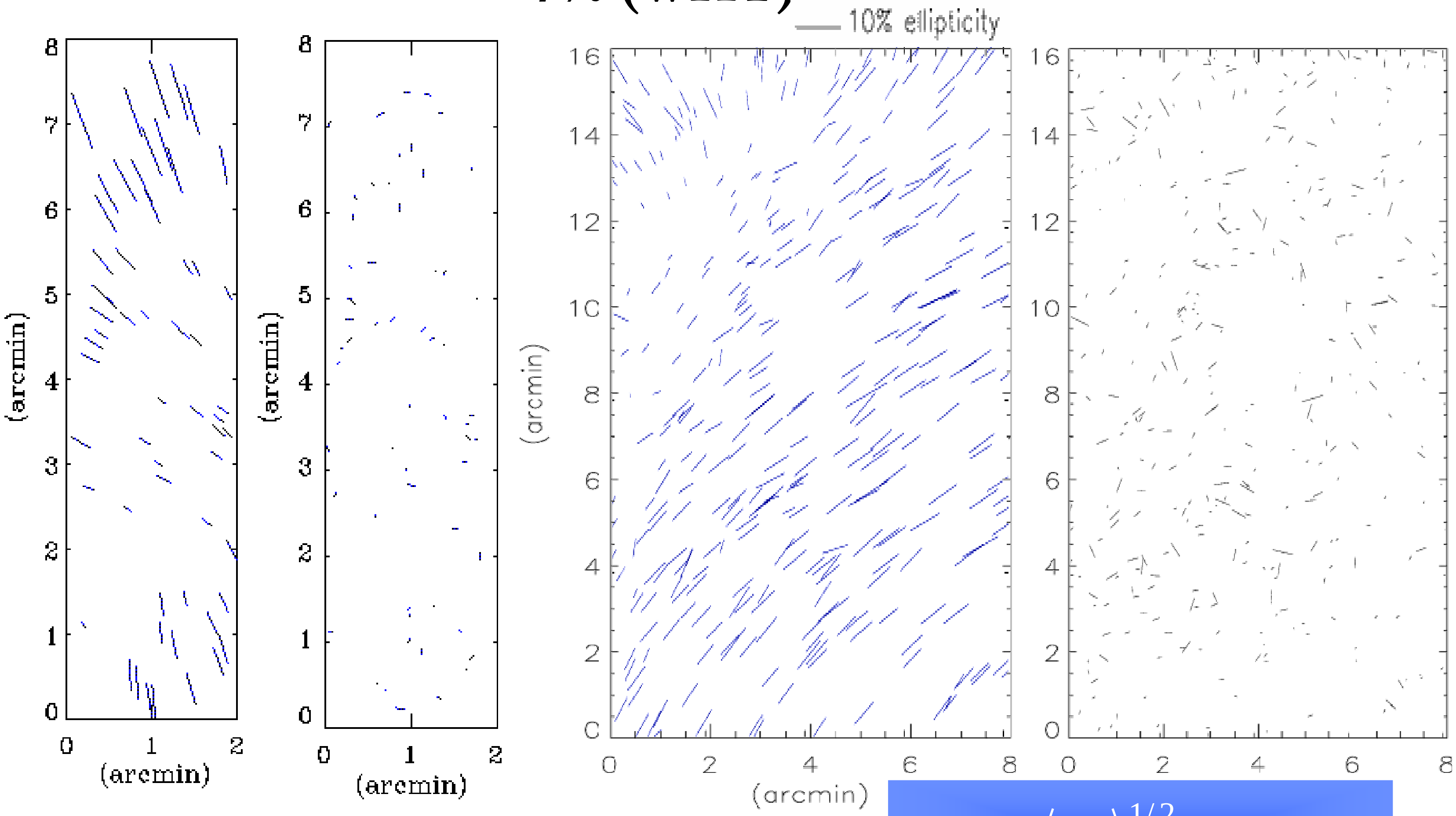


Cameras have instrumental distortion at ~0.3% level (c.f cosmic signal 1%) which can be mapped via dithered imaging if it is stable

(Bacon et al 2002, WHT prime focus)

~~Un~~corrected stellar ellipticities (poor tracking)

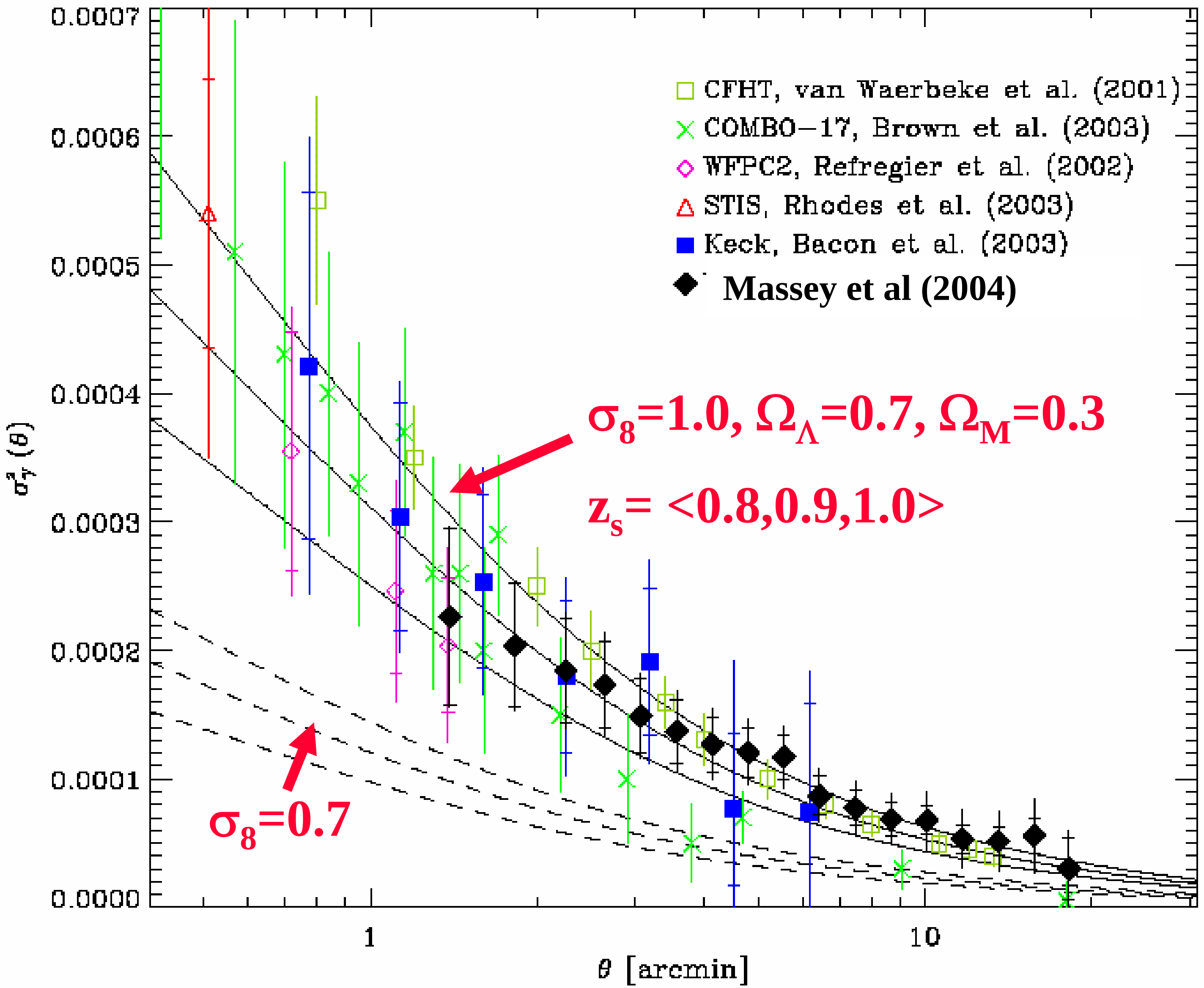
$$\left\langle \varepsilon_*^2 \right\rangle^{1/2} \approx$$ **3·9% (Keck)**
7% (WHT)



So apply this to extended sources…

$$\longrightarrow \left\langle \varepsilon_*^2 \right\rangle^{1/2} = 0{\cdot}1\%$$

Shear Variance from Surveys (2001-04)



Statistical measures constrain joint probability of Ω_M, σ_8

CFHT/MPG 100 deg^2 Survey

Benjamin et al (astro-ph/0703570)

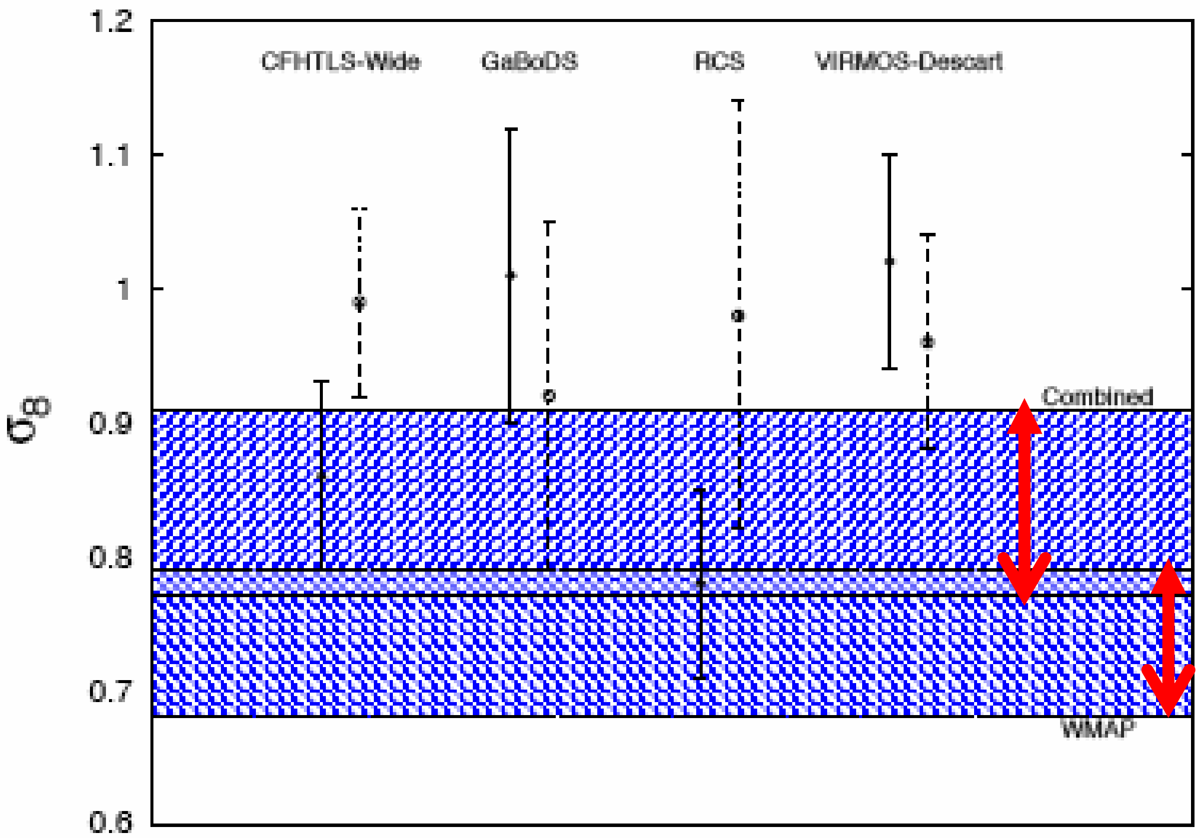
Combination of many surveys from CFHT 3.6m/MPI 2.2m

Enables variance and different instruments to be compared

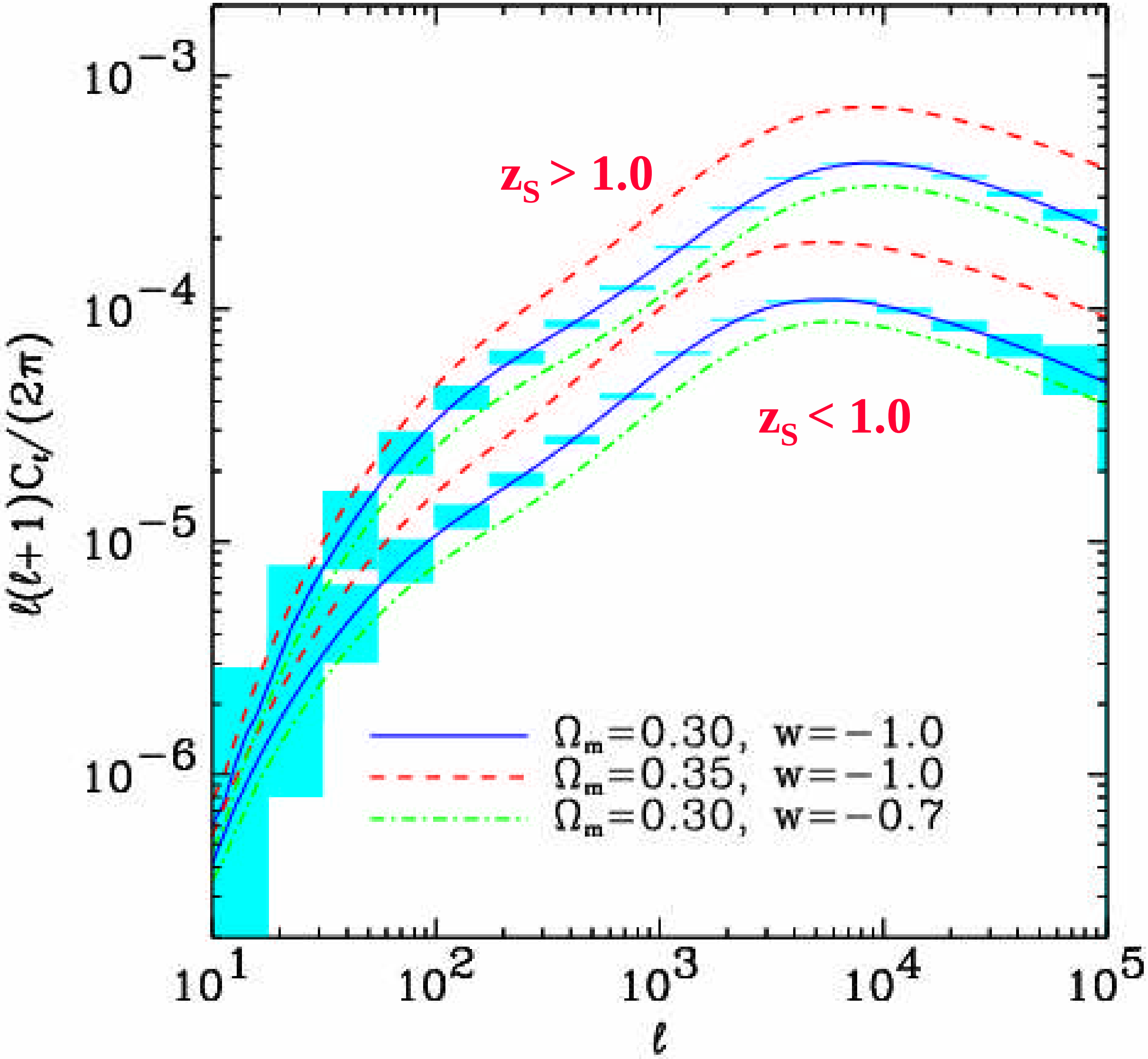
Incorporates calibration bias from simulations (STEP2)

$\sigma_8 = 0.84 \pm 0.05$ for $\Omega = 0.24$

Marginal discrepancy with WMAP



Time Dependence of the DM Power Spectrum

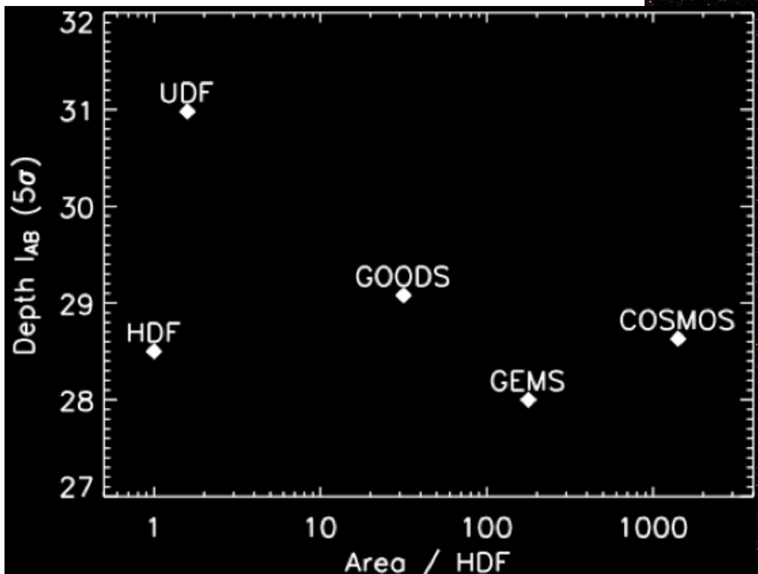


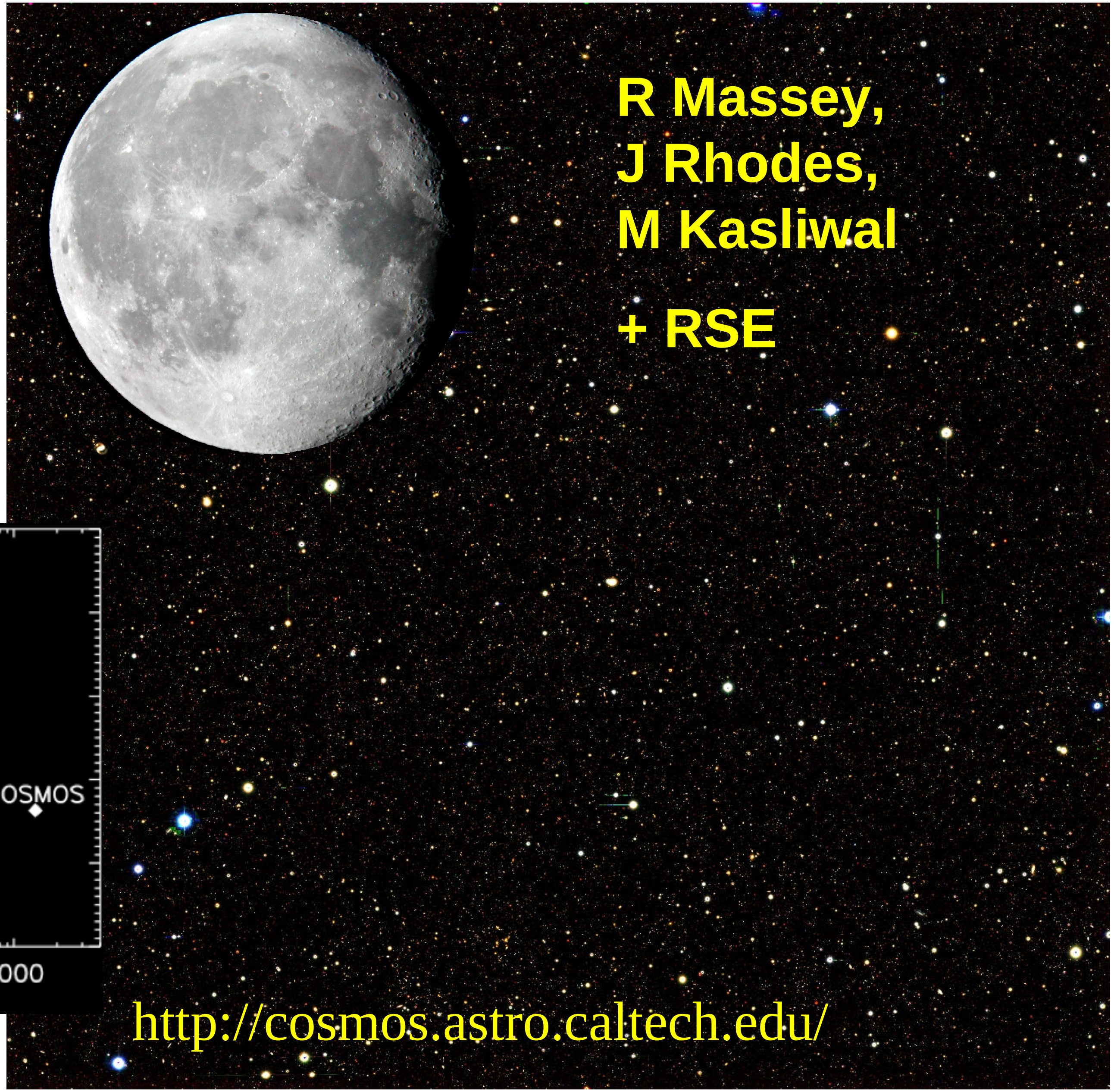
Growth of DM power spectrum is particularly sensitive to dark energy and ***w***.

By comparing cosmic shear for intermediate and very distant background galaxies, it is possible to constrain ***w*** independently of supernovae

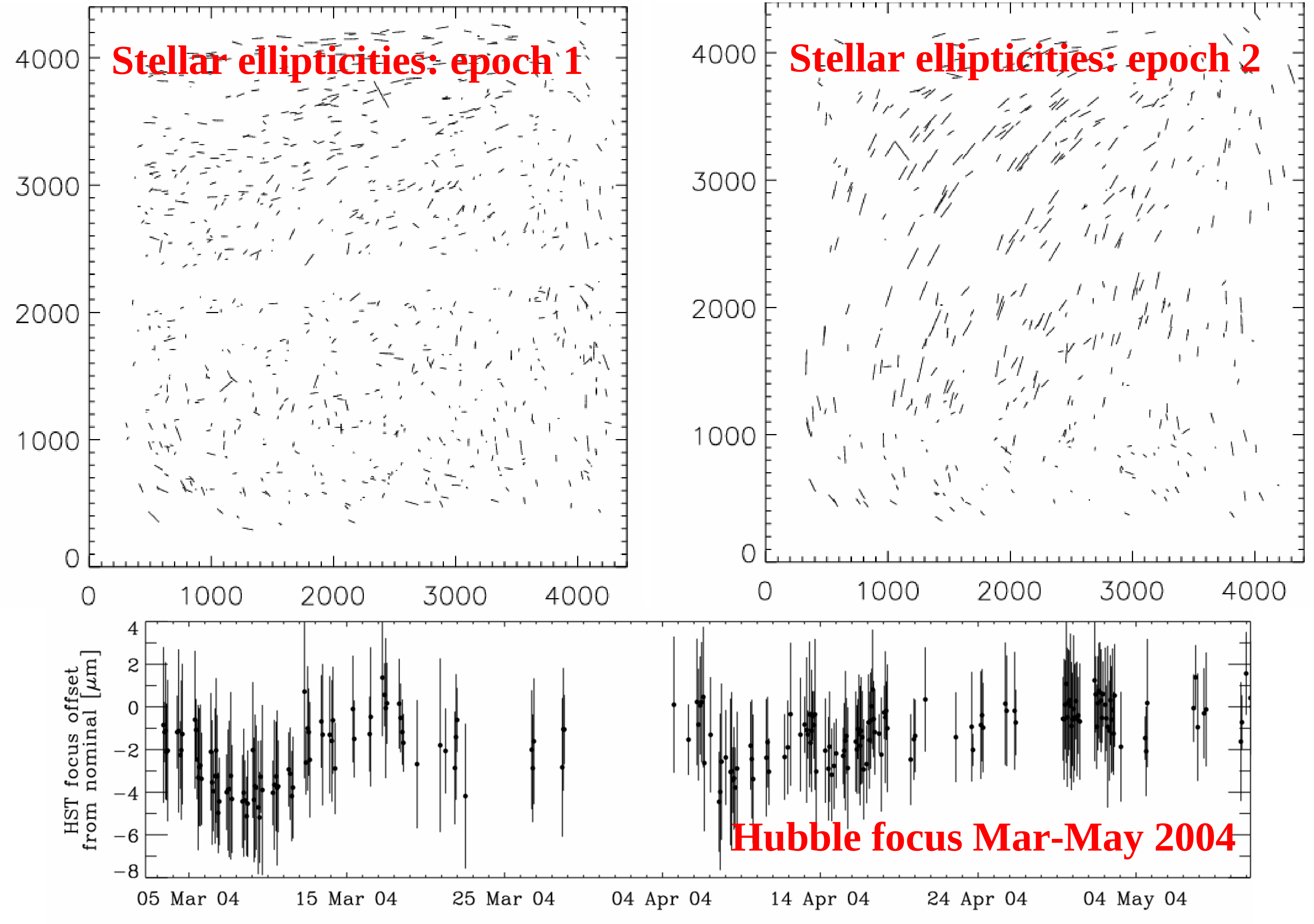
Applications to the Hubble COSMOS Survey

COSMOS:
PI: N. Scoville (Caltech)
Largest HST survey
587 ACS fields
2 deg^2 in F814W
F814W < 26.6 (5σ)
2. 10^6 galaxies
~80 resolved $arcmin^{-2}$

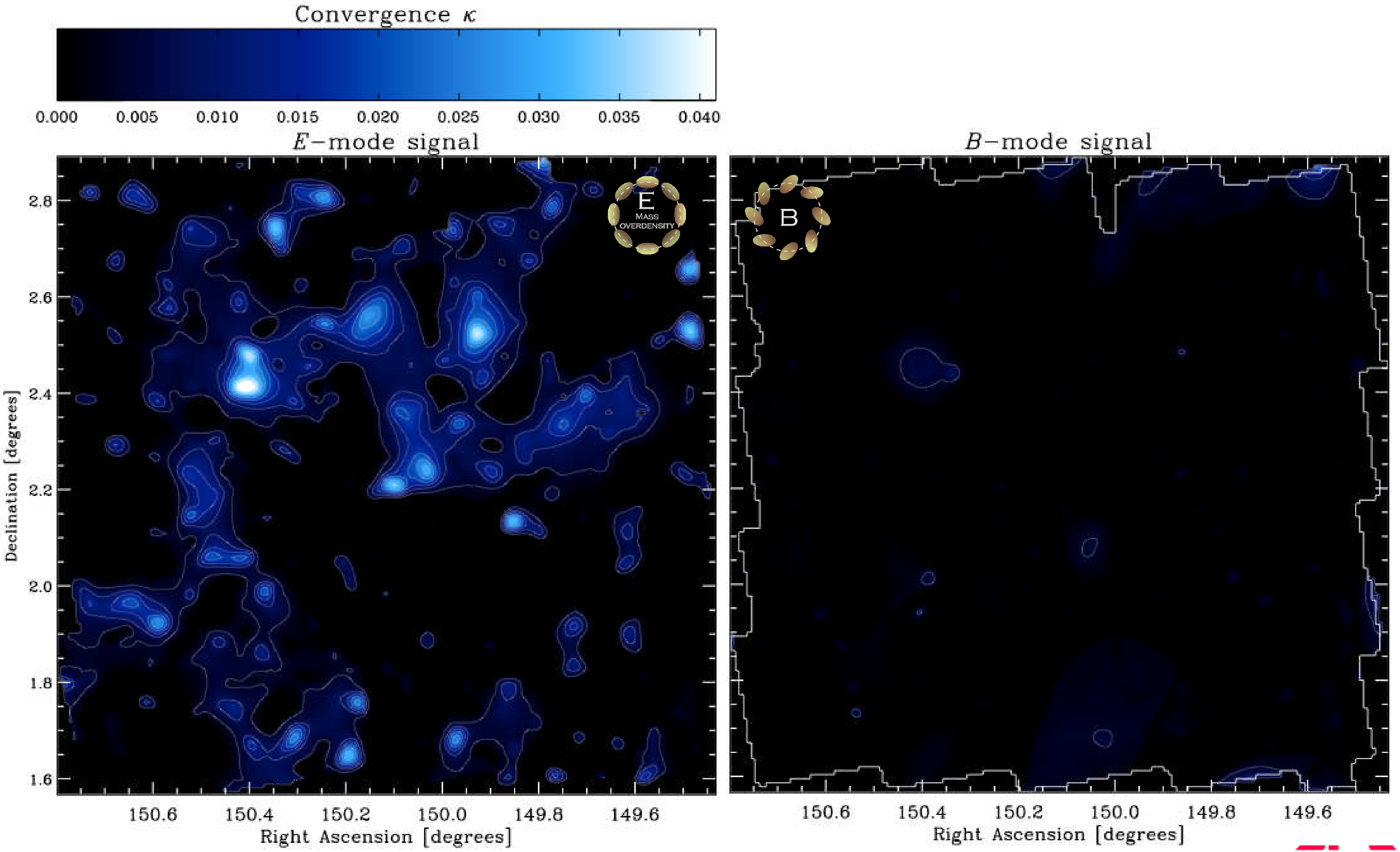




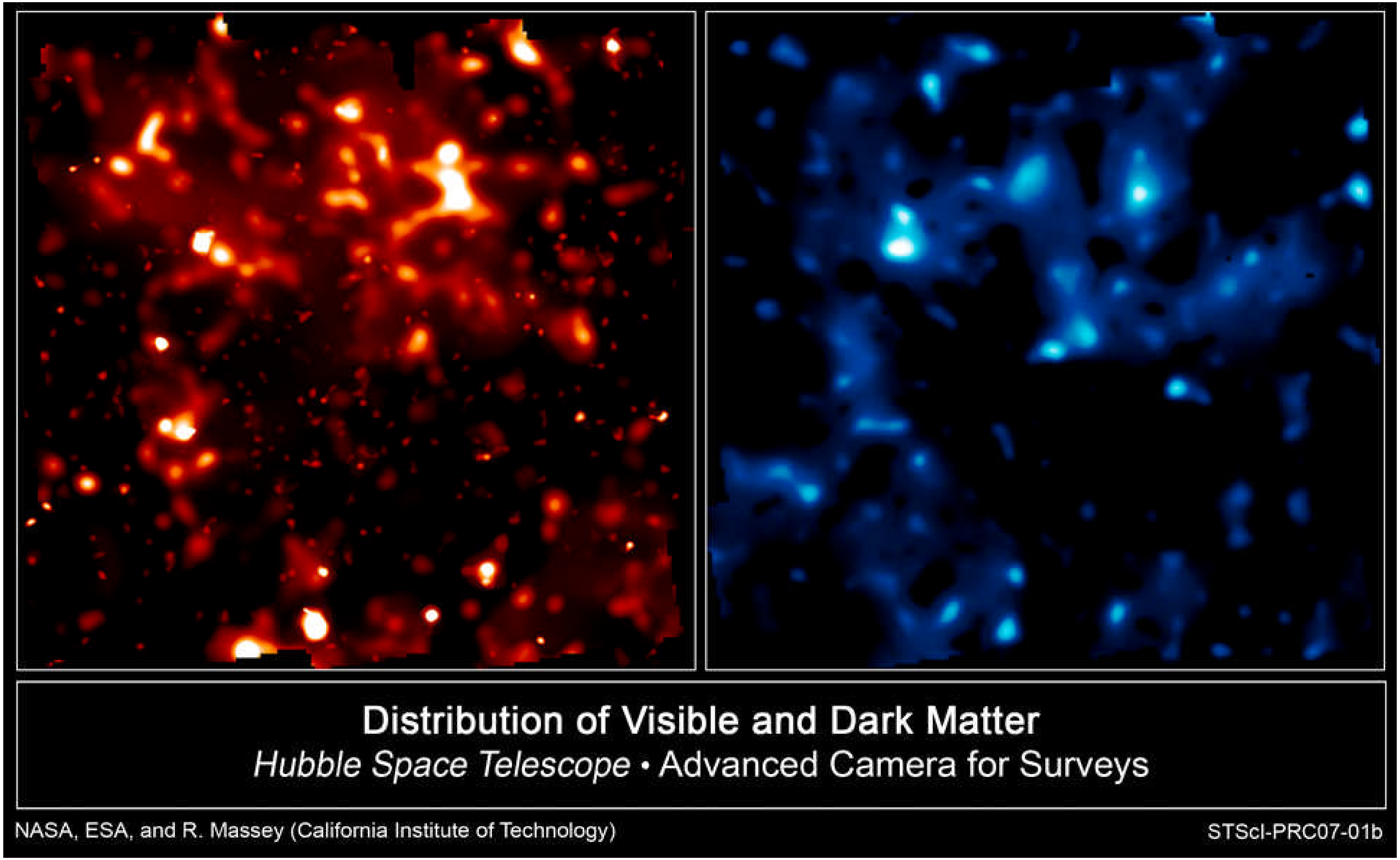
The Hubble Space Telescope PSF Problem



Dark Matter Map: E and B-modes

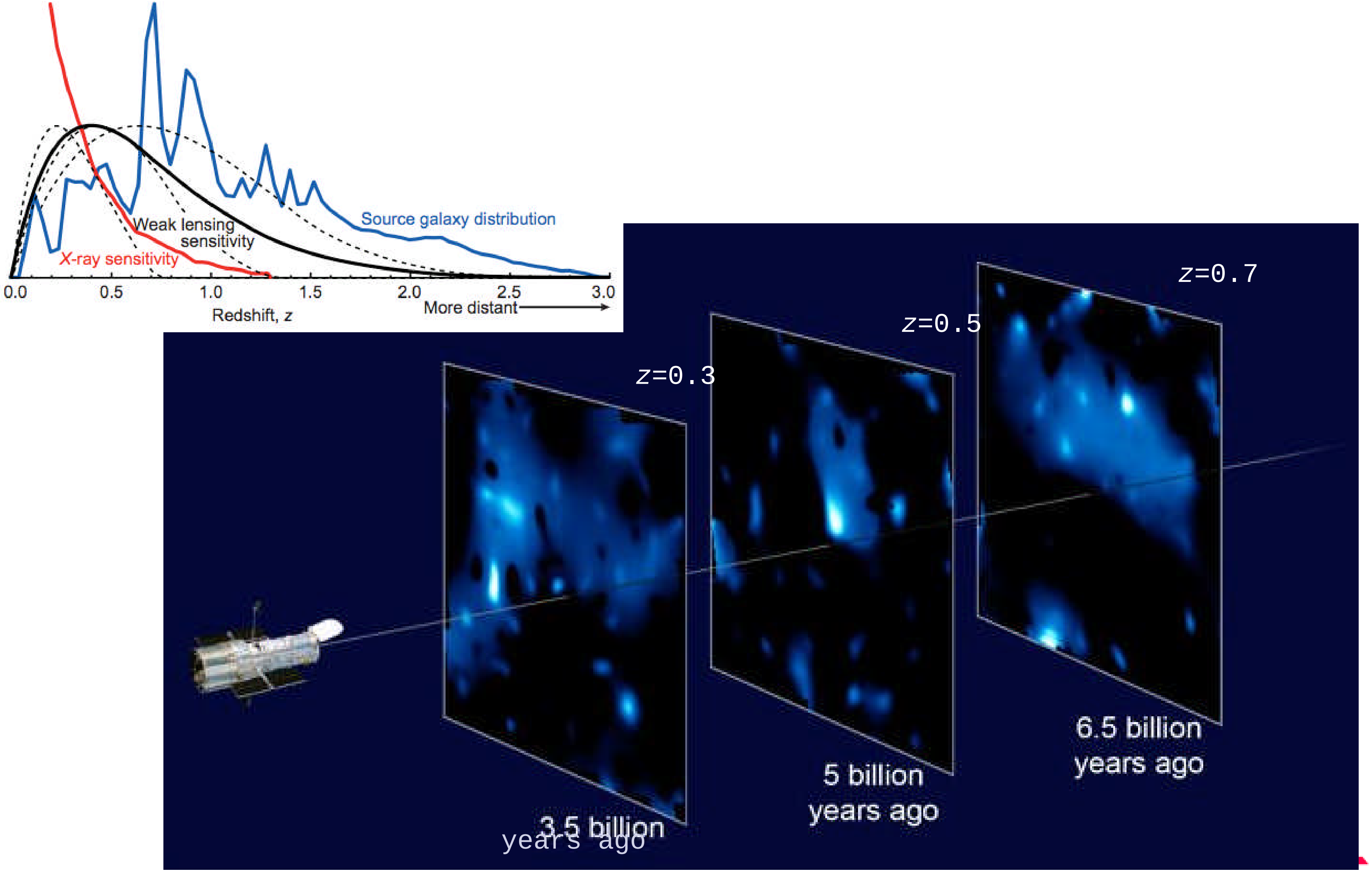


High Fidelity Dark Matter Maps



Massey et al Nature 445, 286 (2006)

Redshift Tomography

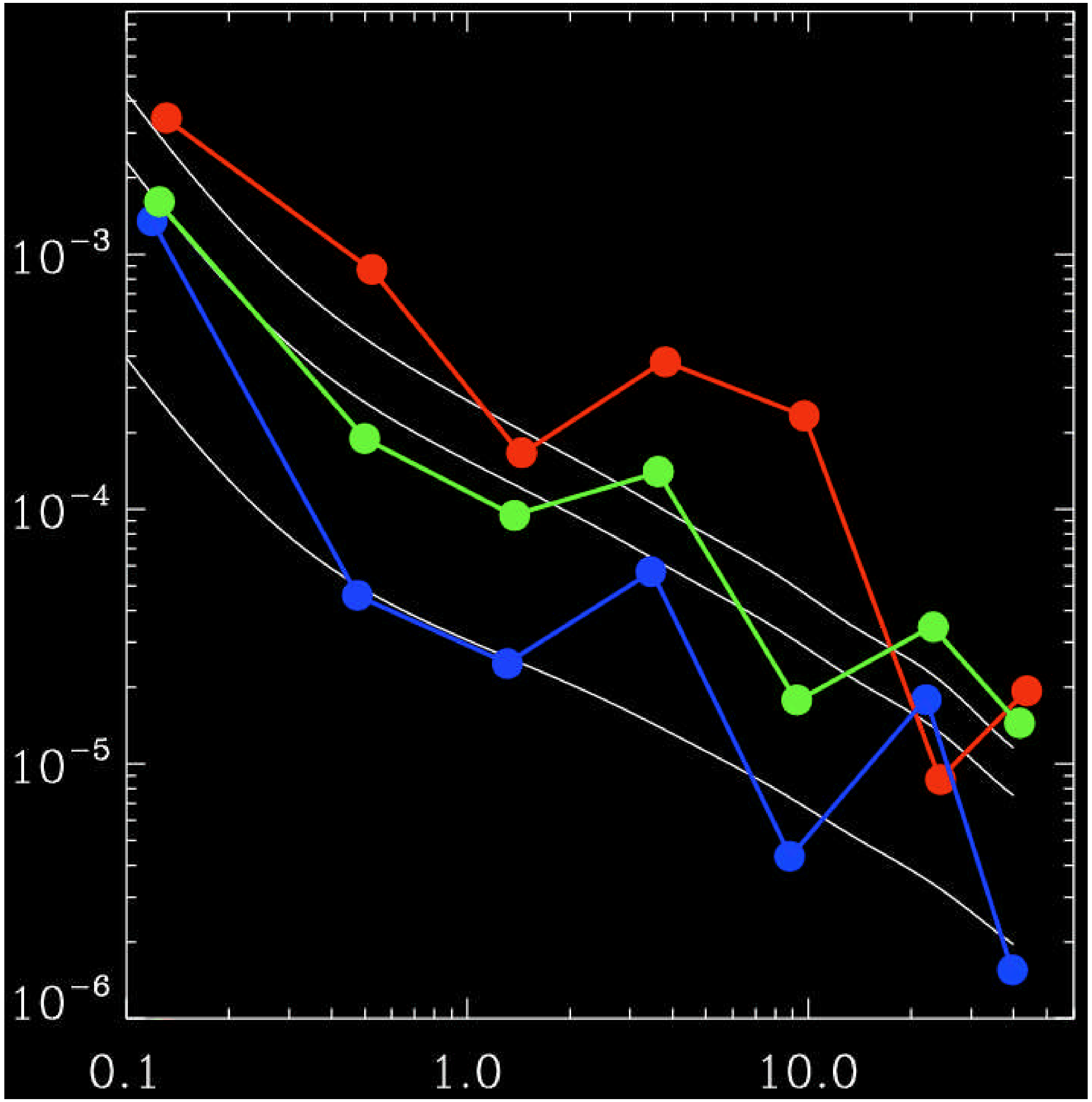


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

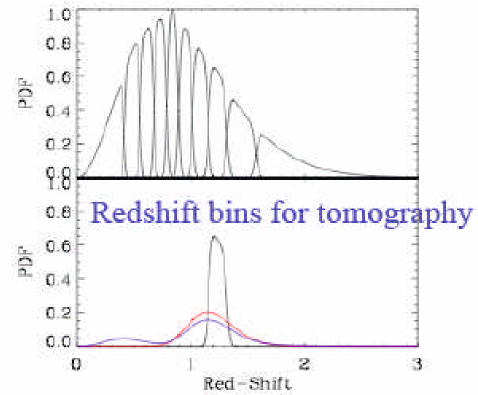
Growth of Structure Detected via Weak Lensing

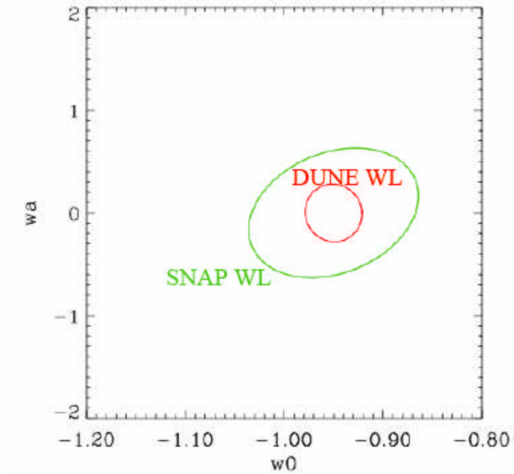
Massey et al Ap J Suppl, 172, 239 (2007)

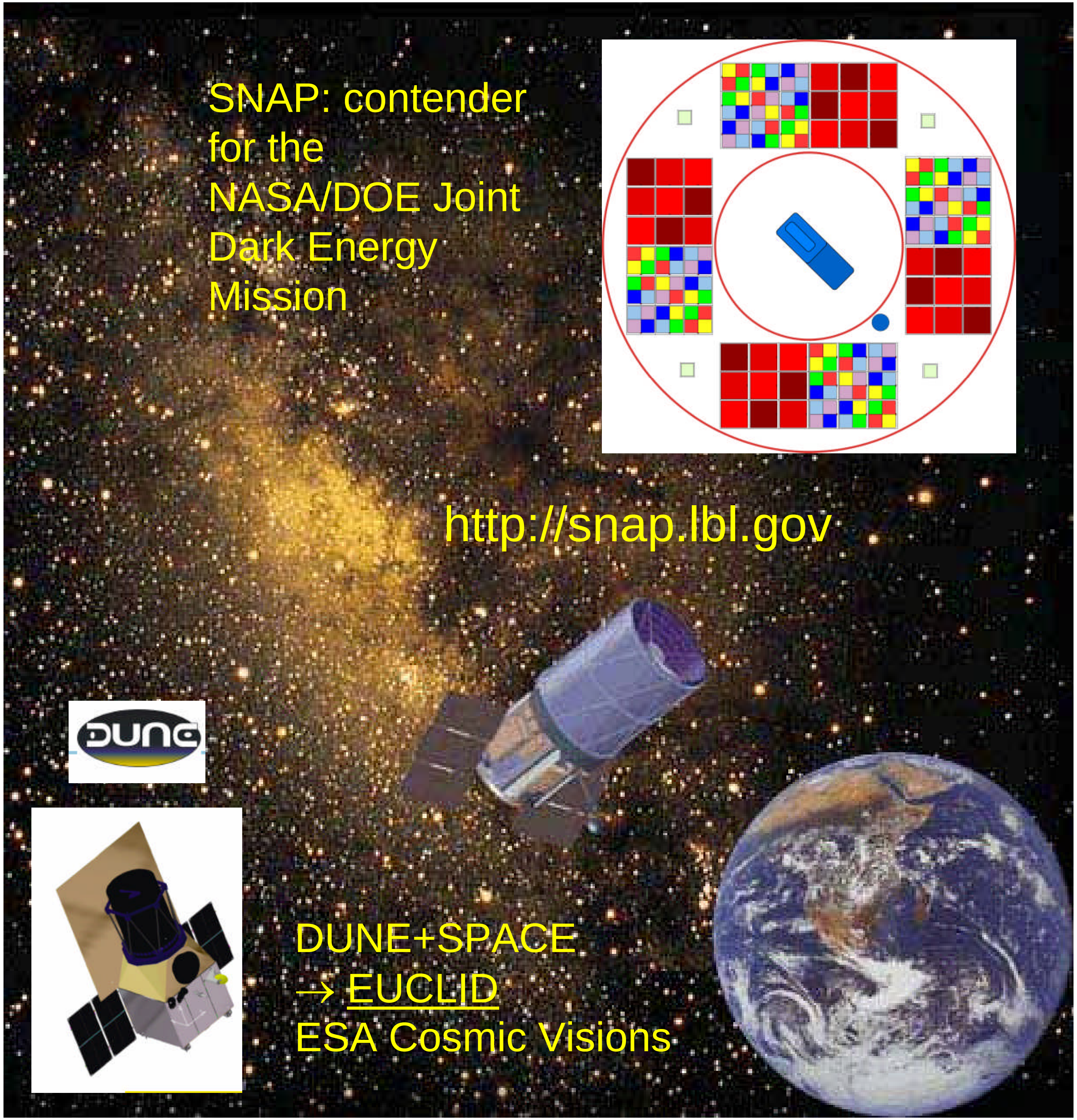


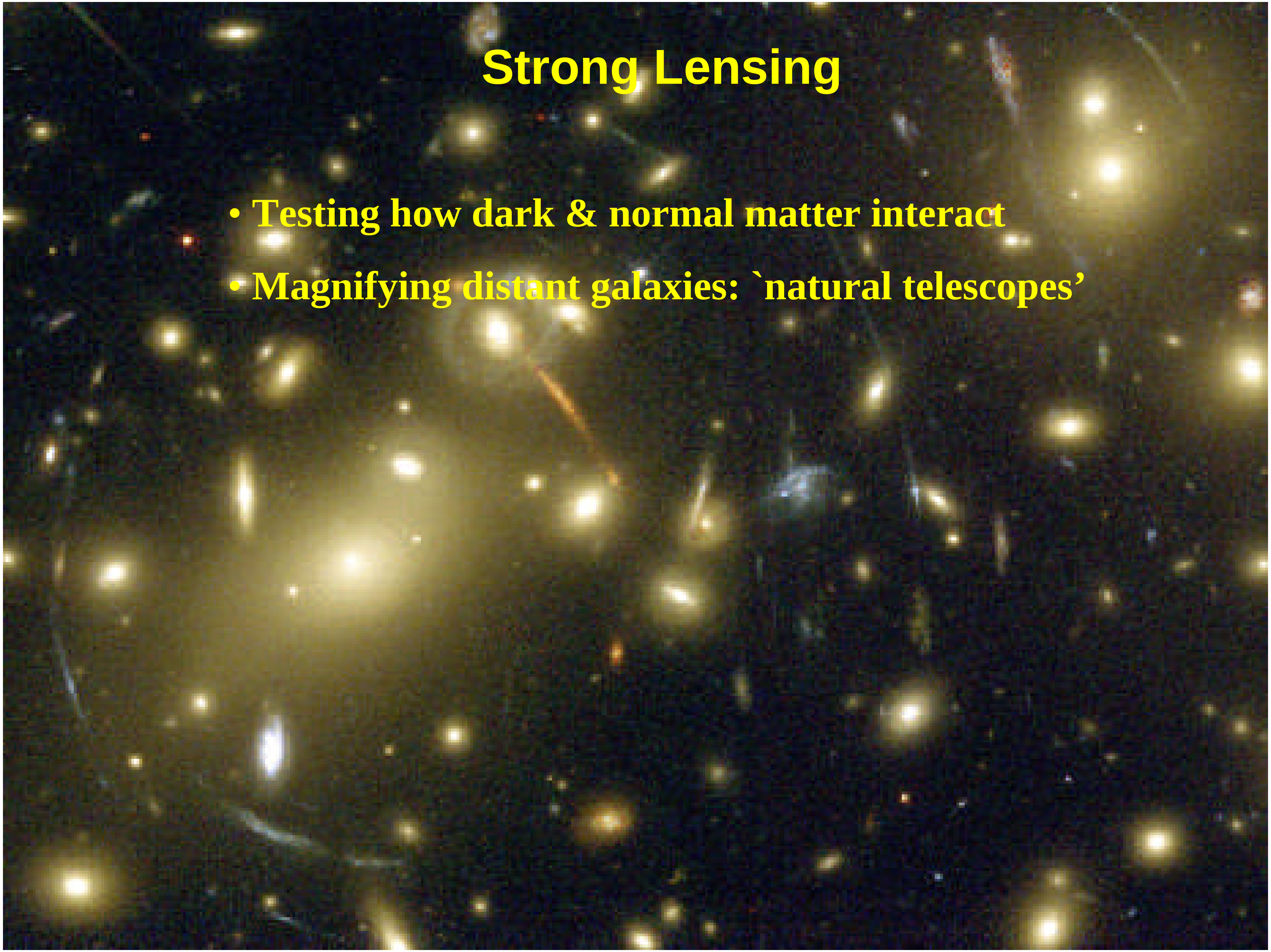
- σ_8=0.866 (+0.085/-0.068) for Ω=0.3
- 3D analysis reduces 2D statistical errors ×3

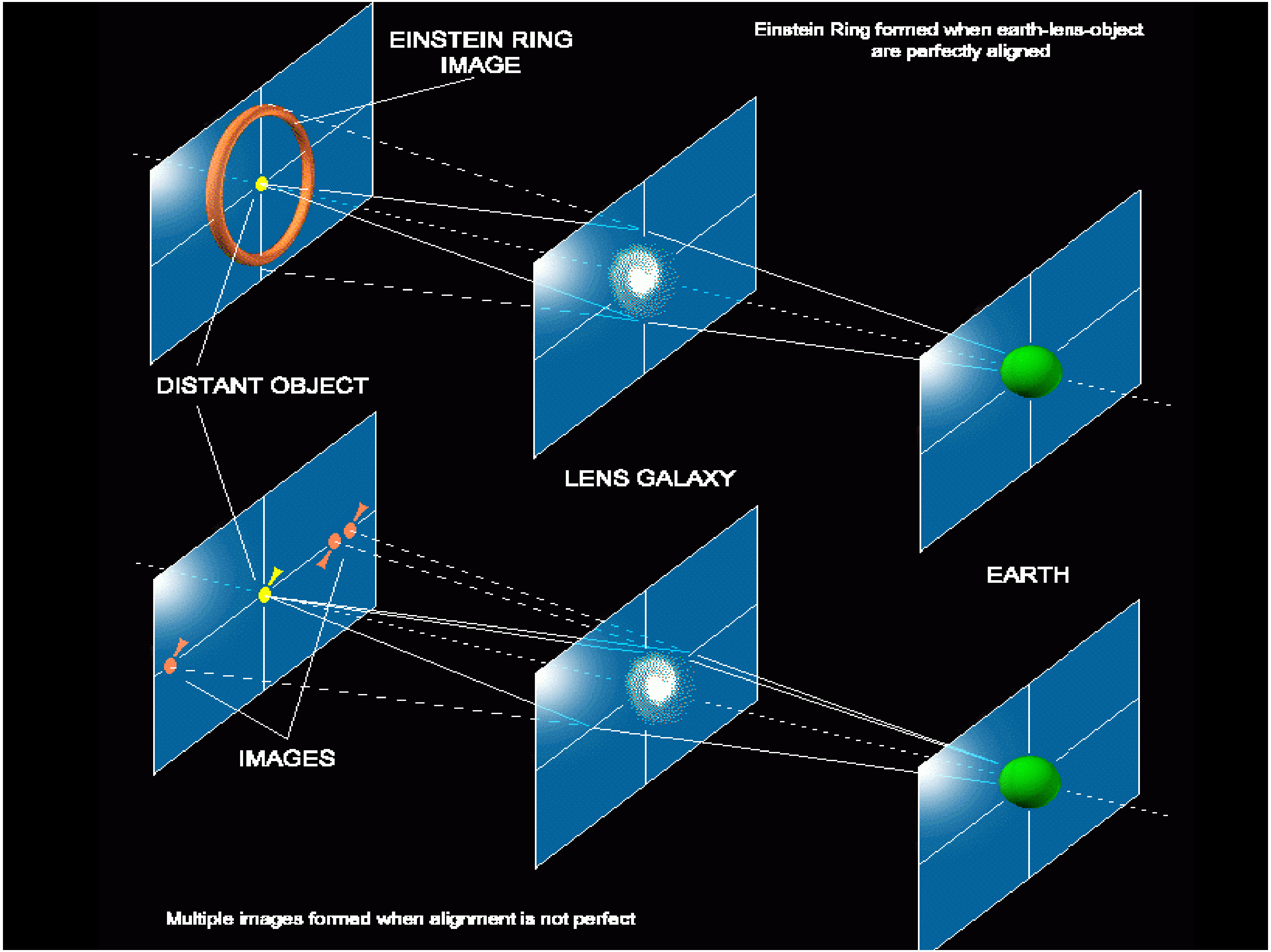
Future Space Missions








Strong Lensing
• Testing how dark & normal matter interact
• Magnifying distant galaxies: `natural telescopes’

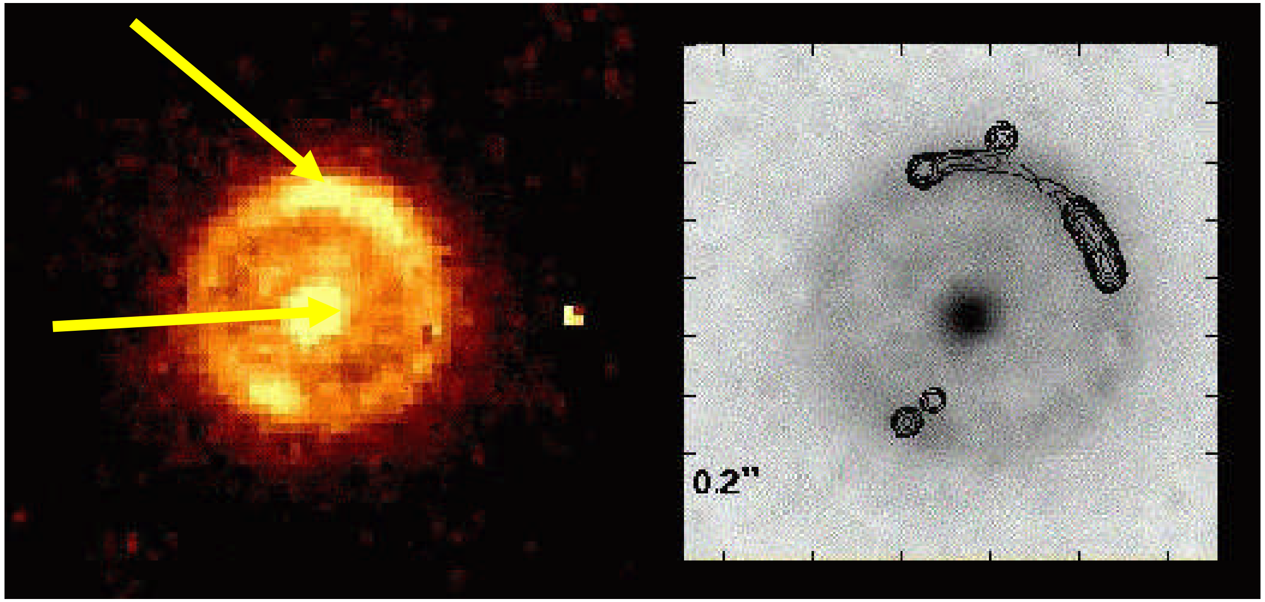


EINSTEIN RING IMAGE
Einstein Ring formed when earth-lens-object are perfectly aligned
DISTANT OBJECT
LENS GALAXY
EARTH
IMAGES
Multiple images formed when alignment is not perfect

The simplest case: the Einstein ring

ring arising from single background source

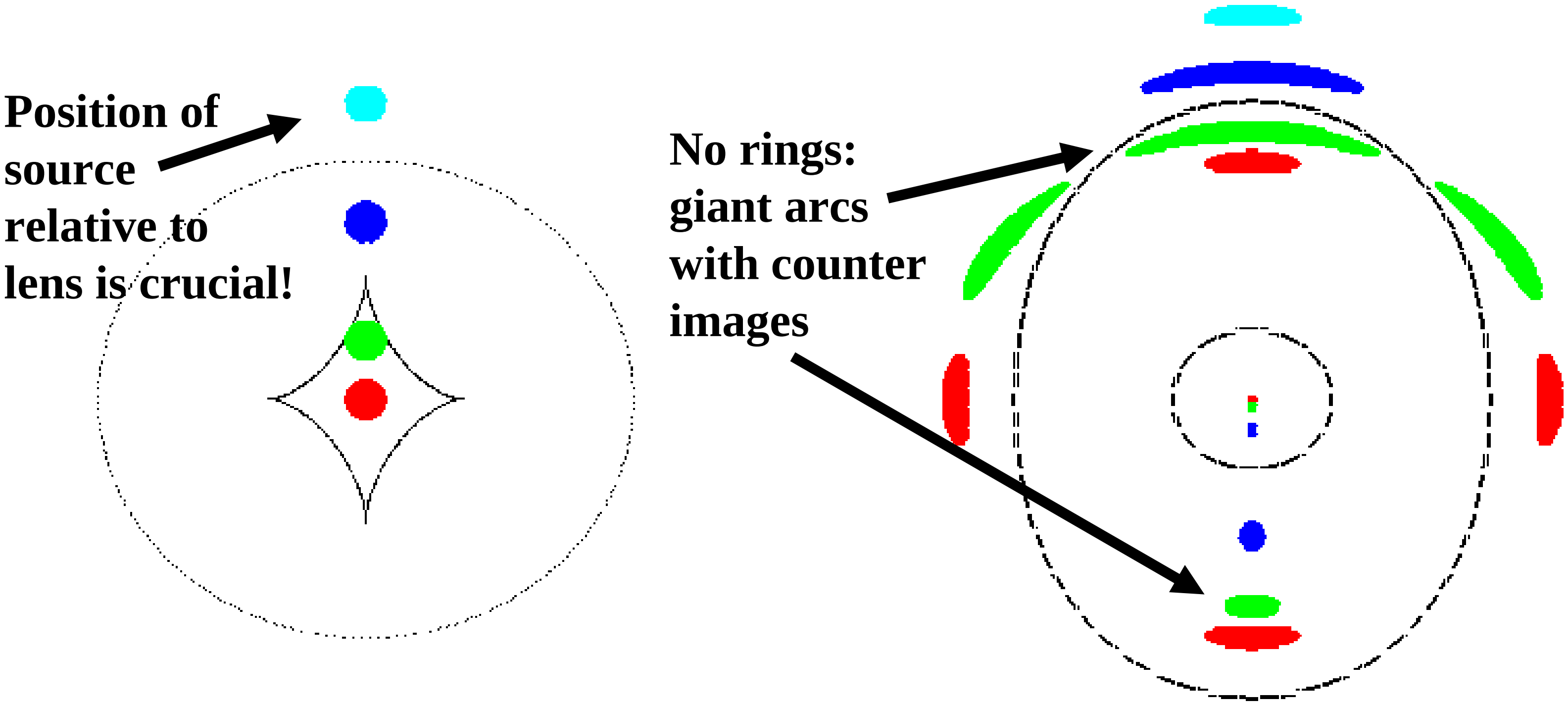
lensing galaxy



imperfection leads to structure in ring

For a compact strong lens aligned with a background source, a ring of light is seen at a radius depending on the geometry and the lens mass, i.e. this allows us to measure the mass of the lens

More Complicated Strong Lenses



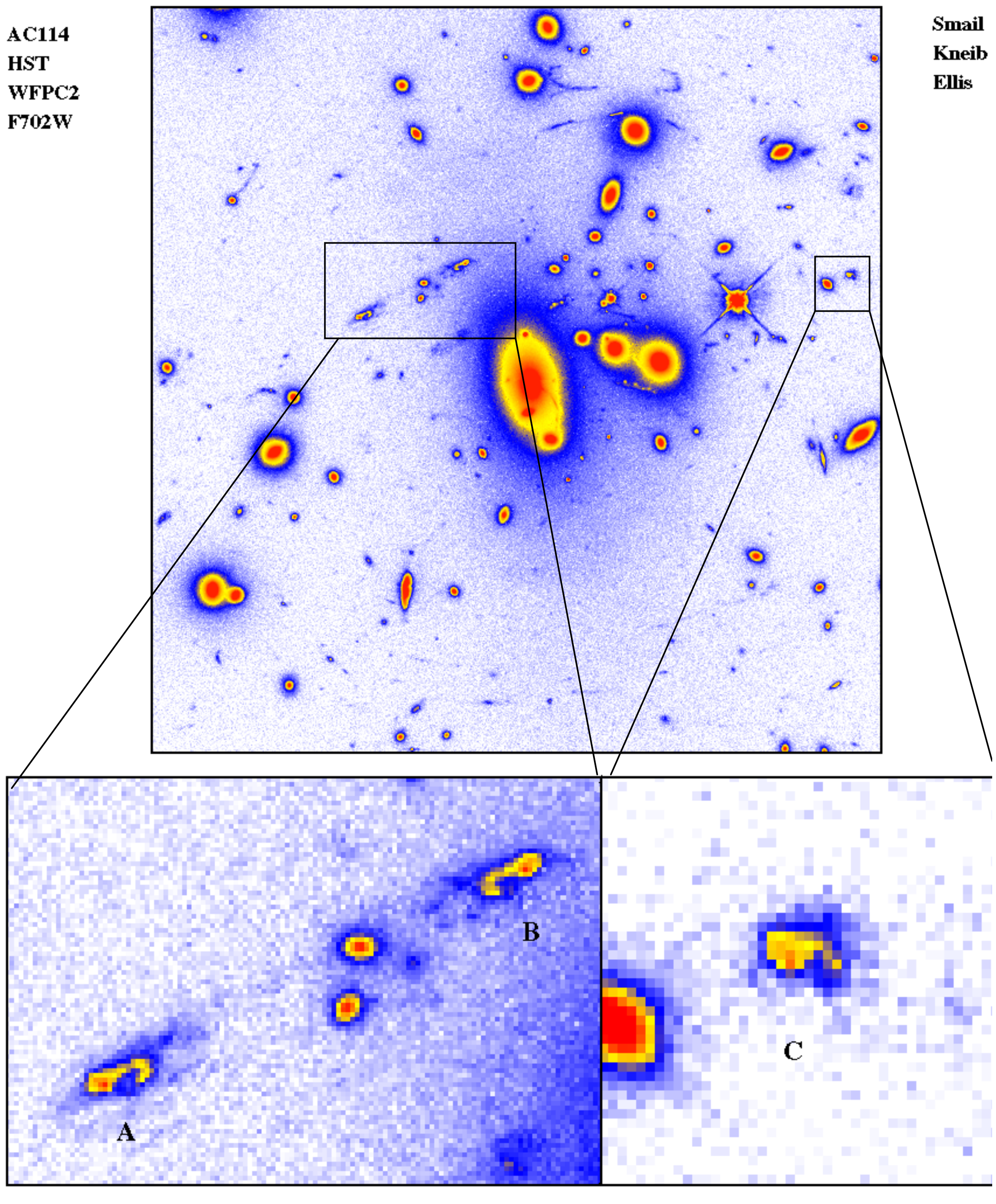
The Real Sky **What Observer Sees**

In case of elliptical lens, no ring is produced, but as background source moves closer in alignment, multiple images, some highly magnified appear – these are known as "giant arcs"

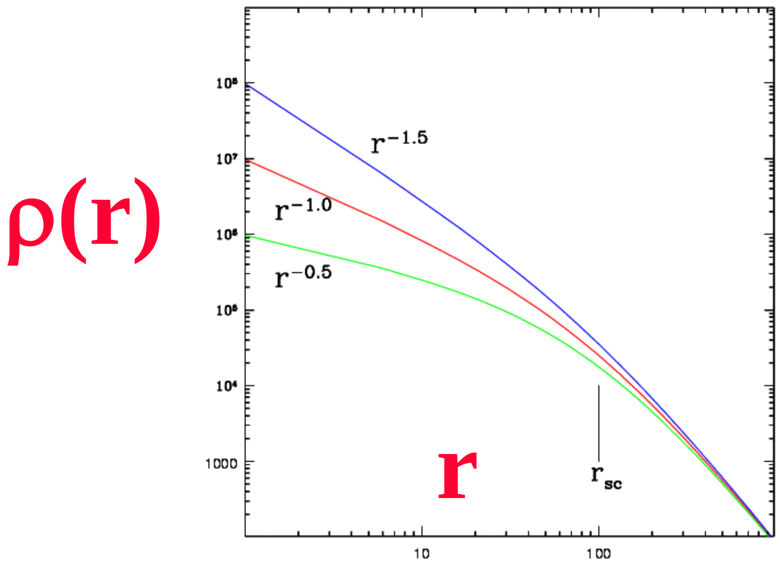
Multiple Images

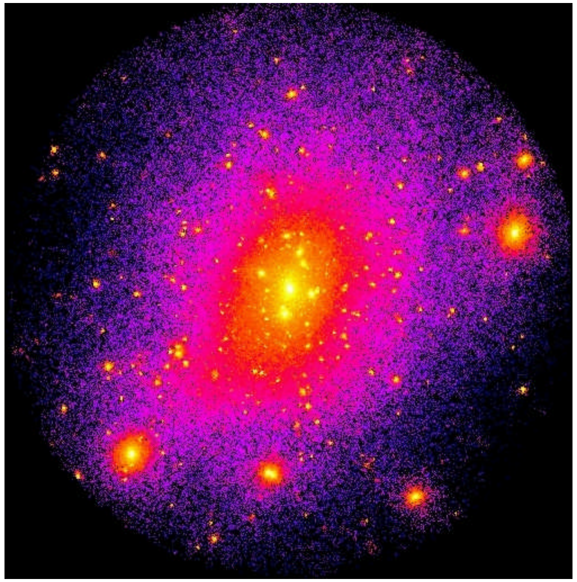
The exquisite resolution of Hubble locates same source seen in 3 different locations!

This is particularly informative if the distances to the lens and the source can be determined as it tells us how lensing matter is distributed in the cluster.



Universal Dark Matter Profile?





- **Dark matter is thought to be `cold': doesn't interact with normal matter.**
- **Simulations suggest it's distributed in clusters via a simple power law**

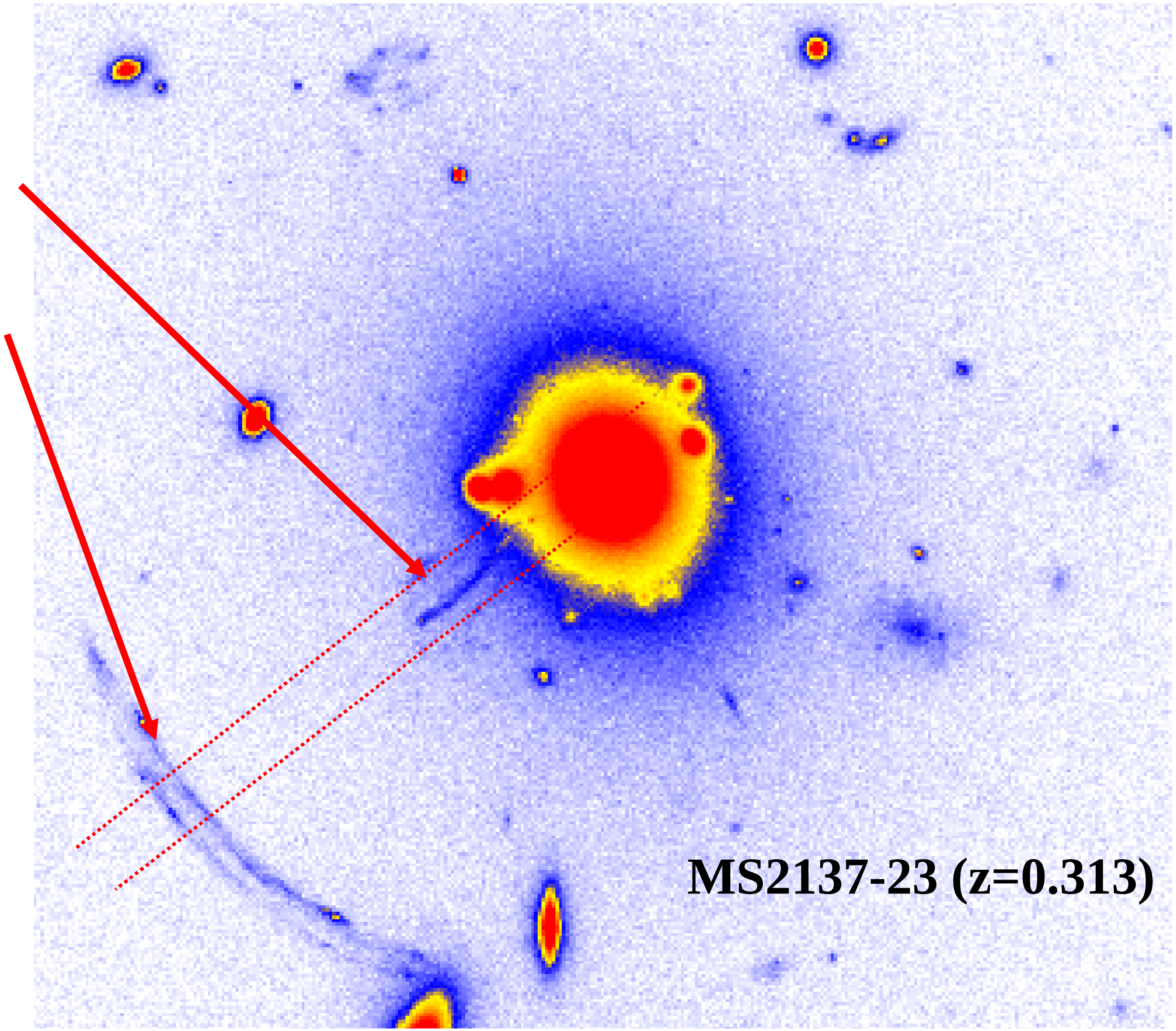
$$\rho_D \propto r^{-\beta}$$

with a "universal" slope β on small scales: $1.0 < \beta < 1.5$

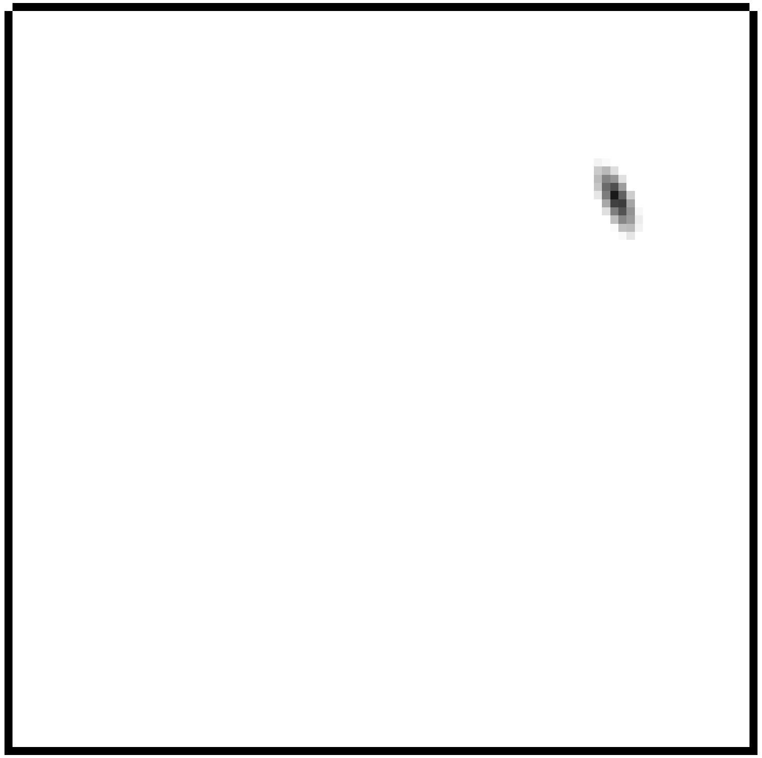
- **Observational verification remains controversial**
- **Can strong lensing test whether DM is truly non-interacting?**

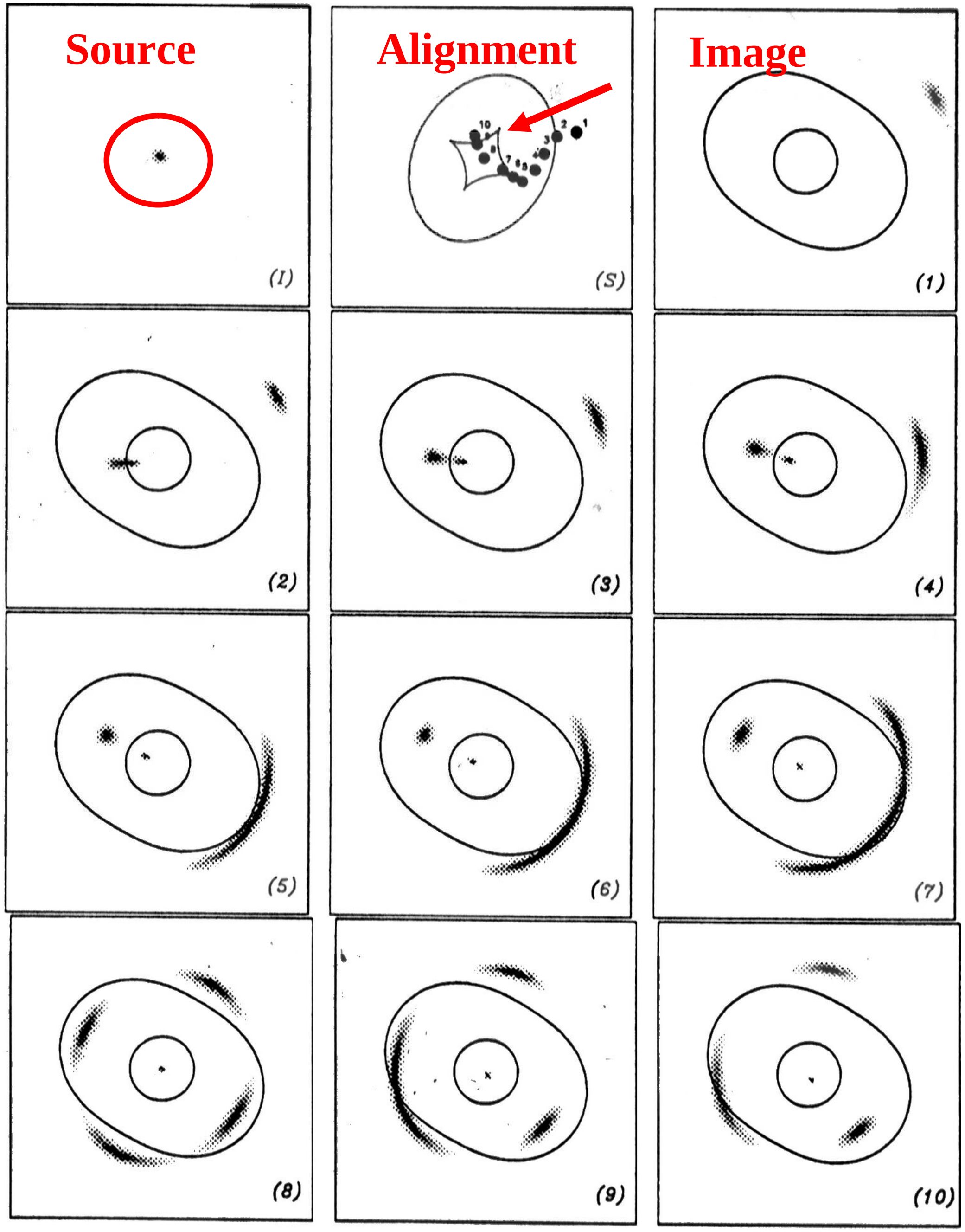
Mass profiles in cluster cores

Presence of *radial and tangential* arcs of known z strongly constrains mass on 20-50 kpc scales



Arcs in an elliptical lens with a core





Tangential: measures enclosed mass

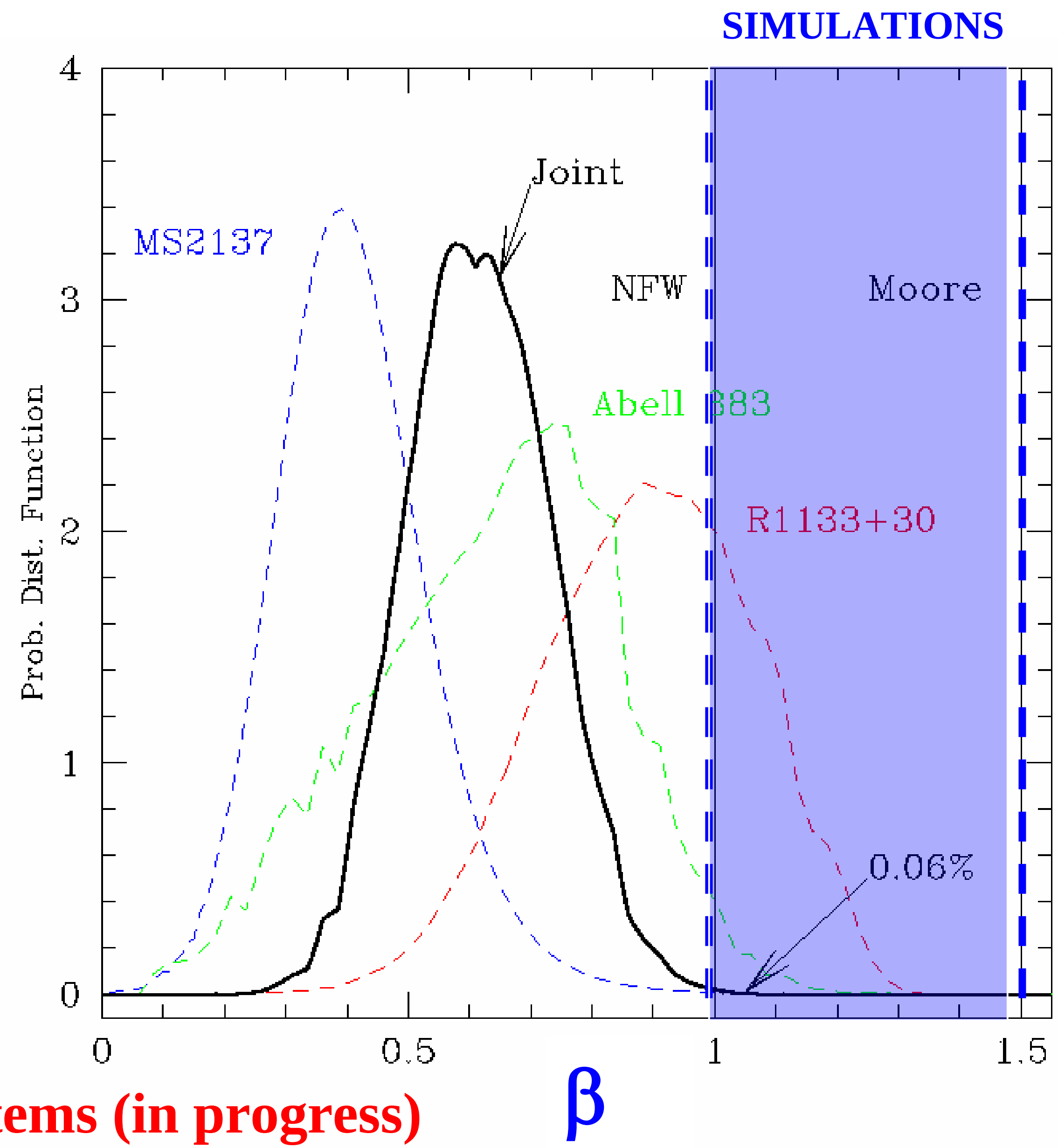
Radial: measures mass derivative

DM Profile: Results So Far

Constraining joint distribution of DM and normal matter on small (50-100 kpc) scales

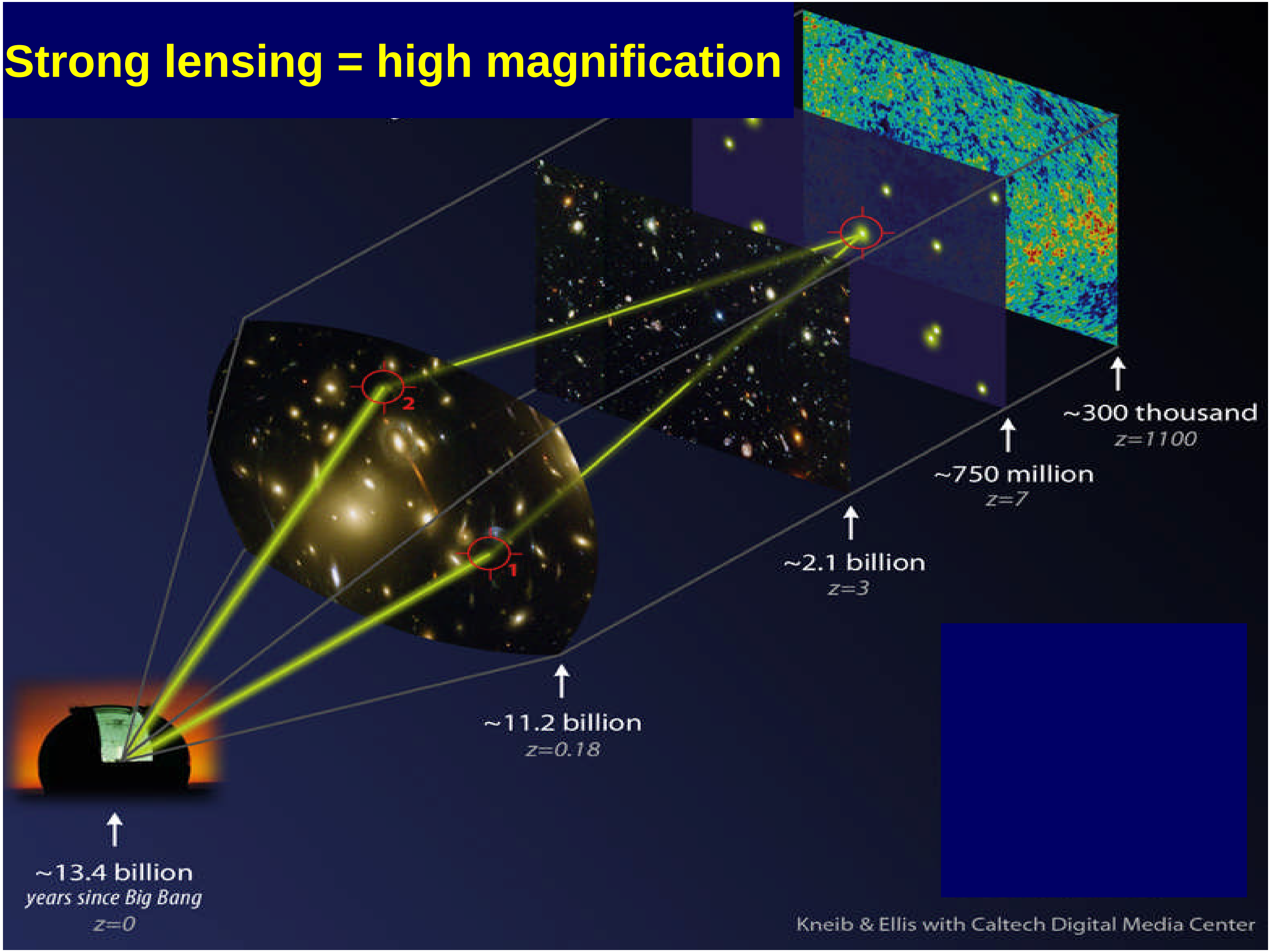
First results (3 cases) challenge cold dark matter simulations - flatter profiles than expected!

NB: baryon infall should steepens DM distribution

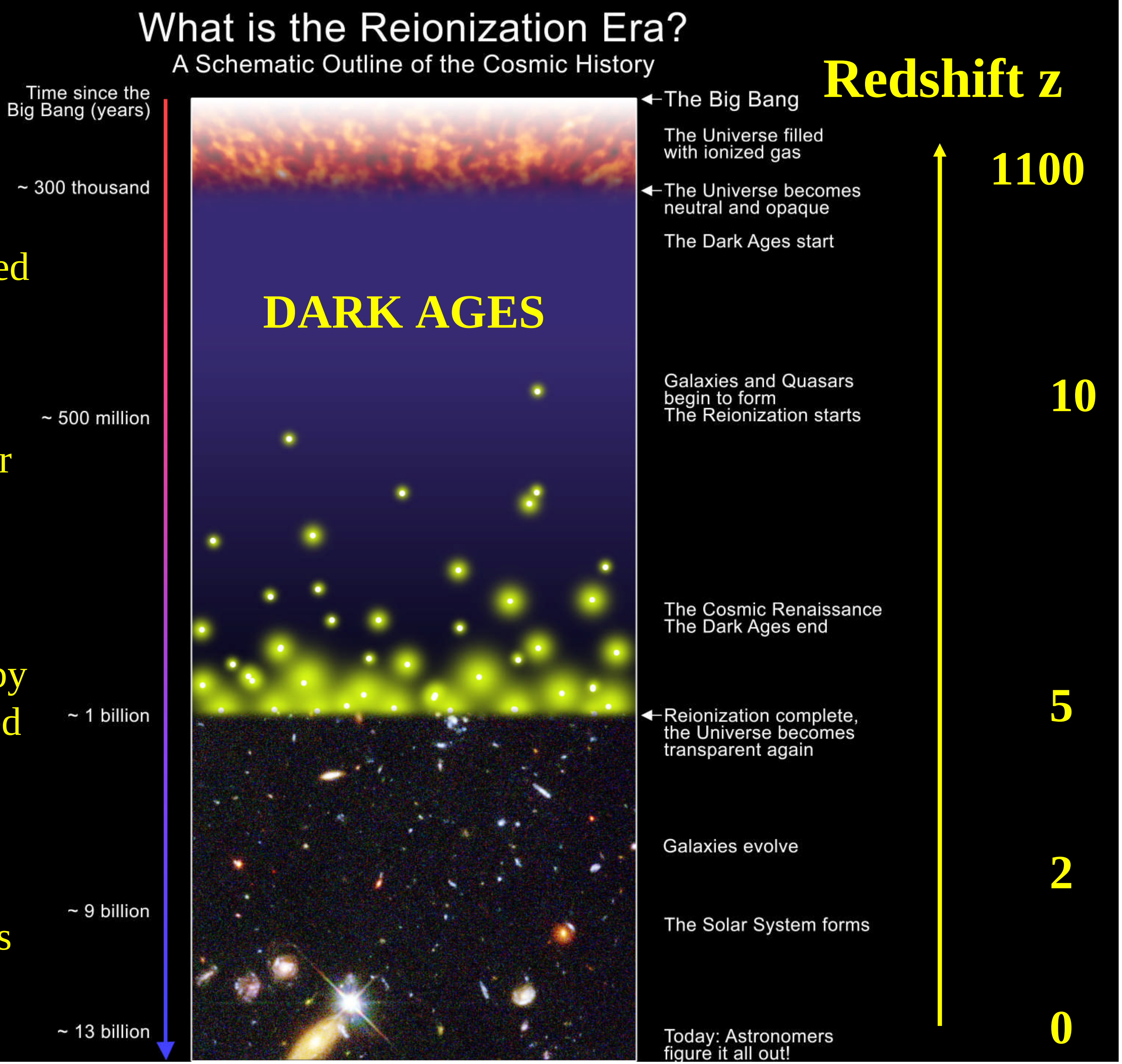


Now extending to 12 systems (in progress)

Strong lensing = high magnification



- After era probed by WMAP the Universe enters the so-called “dark ages” prior to formation of first stars
- Hydrogen is then re-ionized by the newly-formed stars
- How do we explore this era when the sources are so faint?



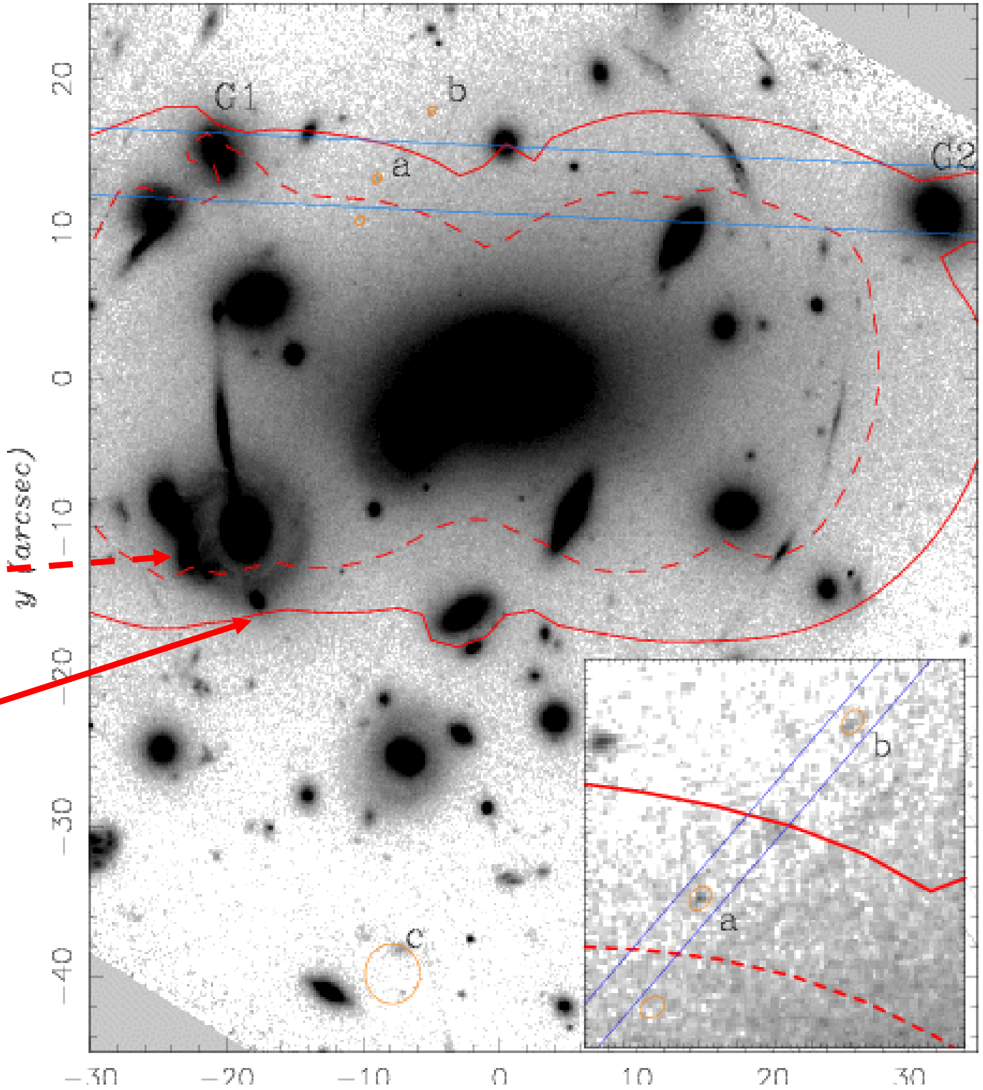
Mapping Regions of High Magnification

From previous spectroscopy the location of the "critical lines" is known precisely for

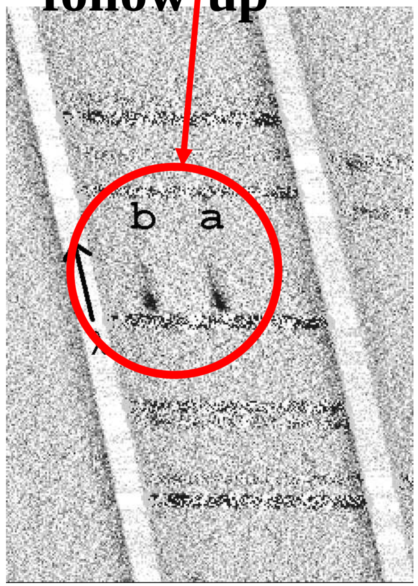
z=1

and for

z=5

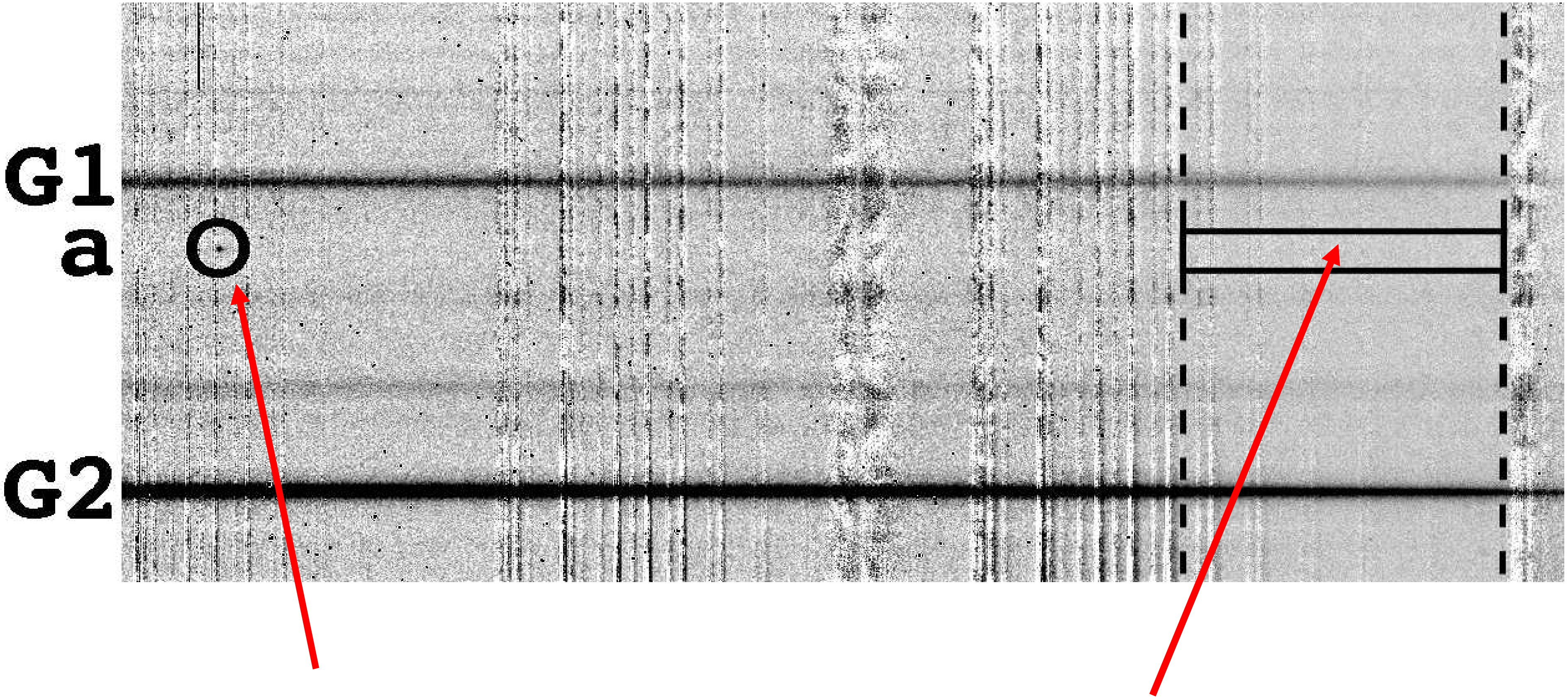


Blind search with low spectral resolution: higher resolution follow-up



Utilizing strong magnification (×10-30) of clusters, probe much fainter than other methods but in small sky fields (<0.1 arcmin^2)

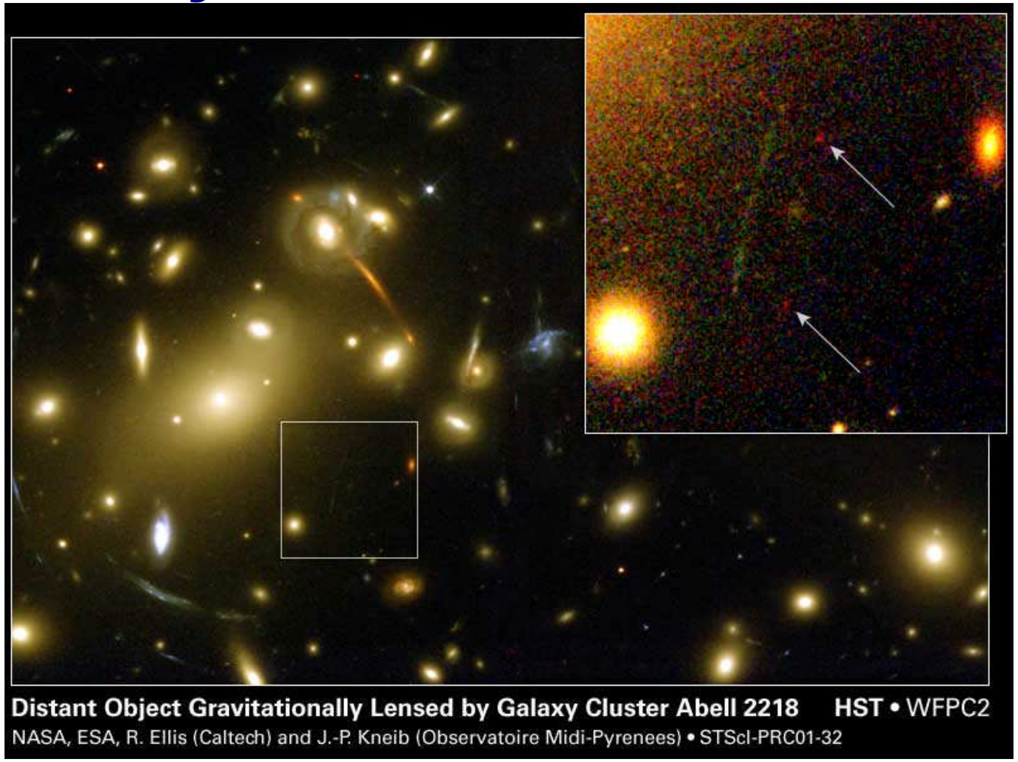
Blind Longslit Search with Keck



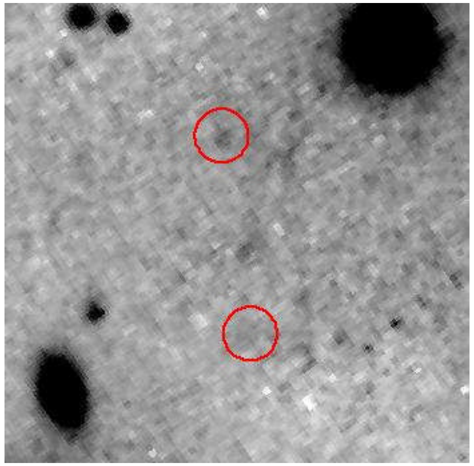
Candidate Lyman alpha (z=5.7) with no detectable stellar continuum

Young Low Mass System at z~5.7

- Magnification ×30 implies the true (unlensed) flux from source is 20 × fainter than could be detected with other techniques
- Hydrogen emission implies source is forming stars at ≈ 0.5 solar mass yr^{-1}
- But faint stellar continuum implies source is young: < 1-2 Myr old
- Forming low mass galaxy

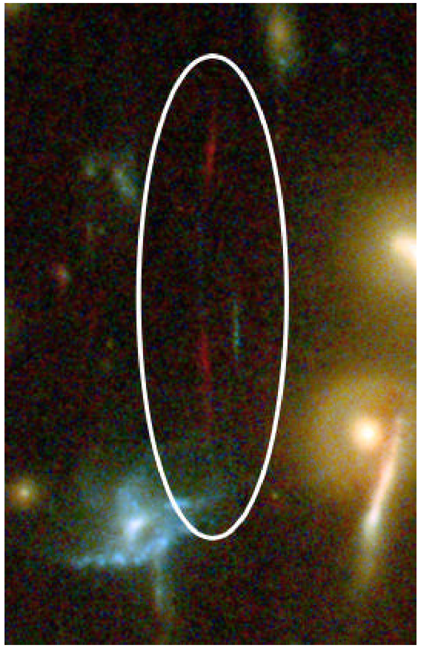


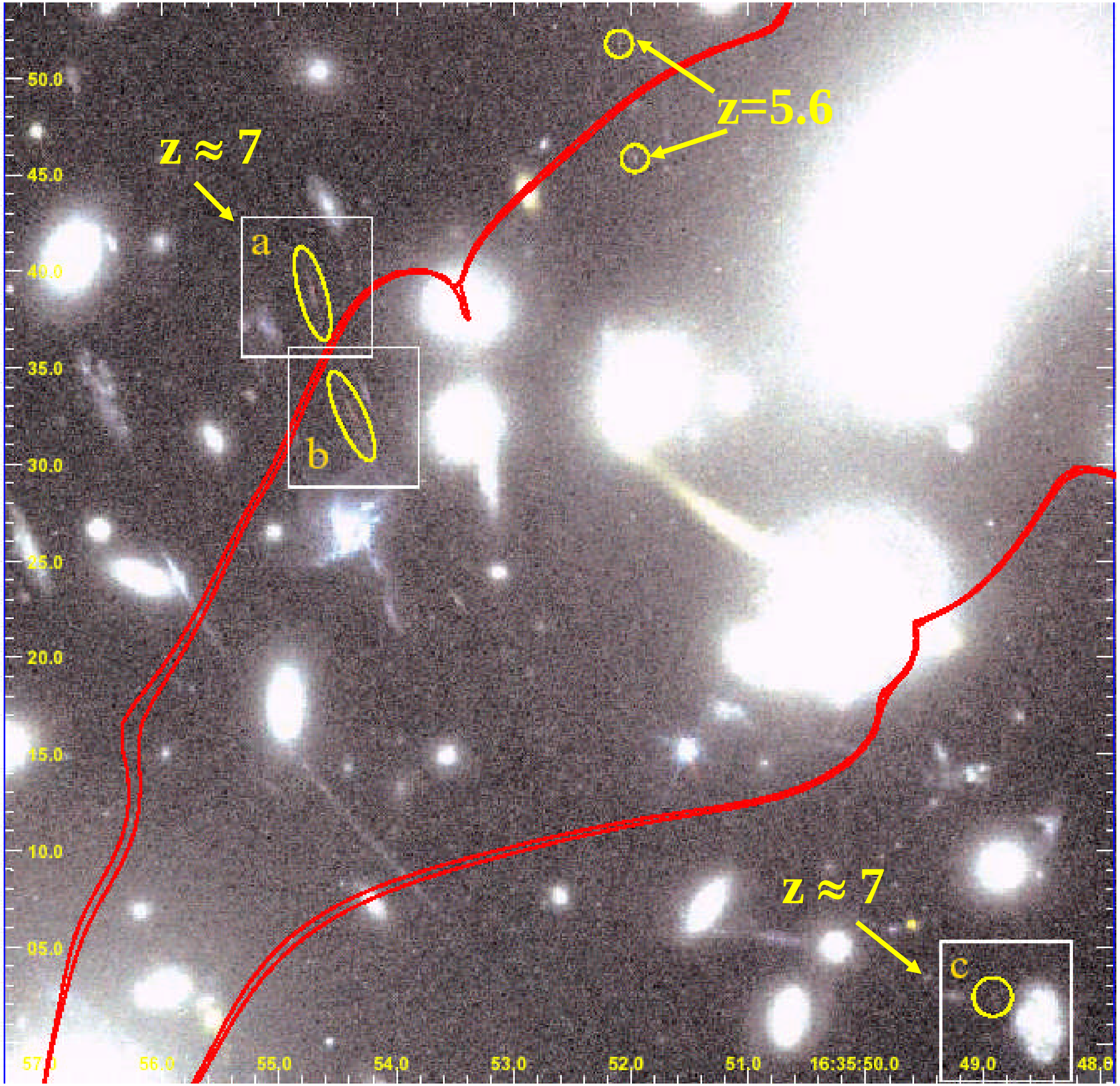
Hubble infrared detection

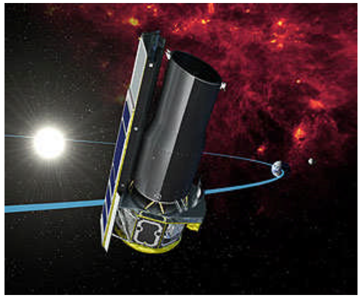


Ellis et al Ap J 560, L119 (2001)

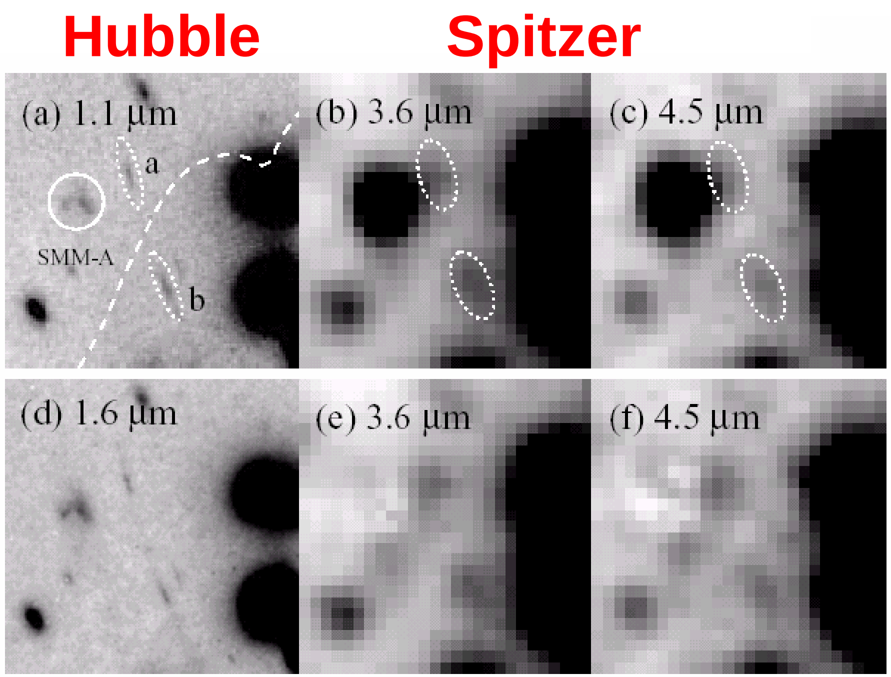
Magnified distant objects viewed thru Abell 2218

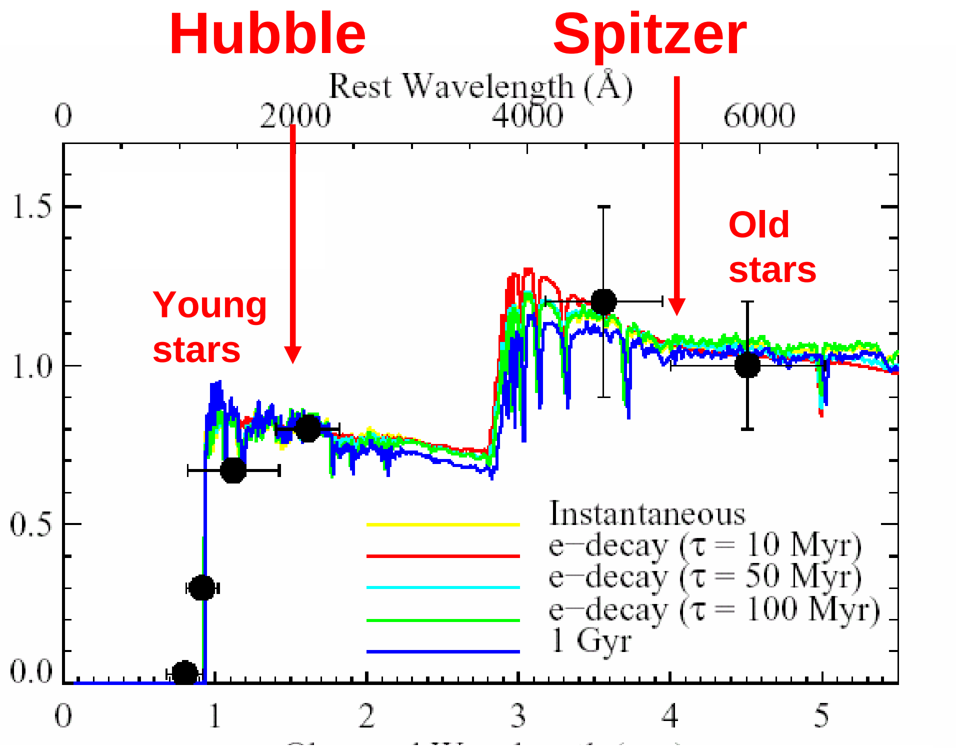






Deciphering Earlier History of z~7 Galaxy





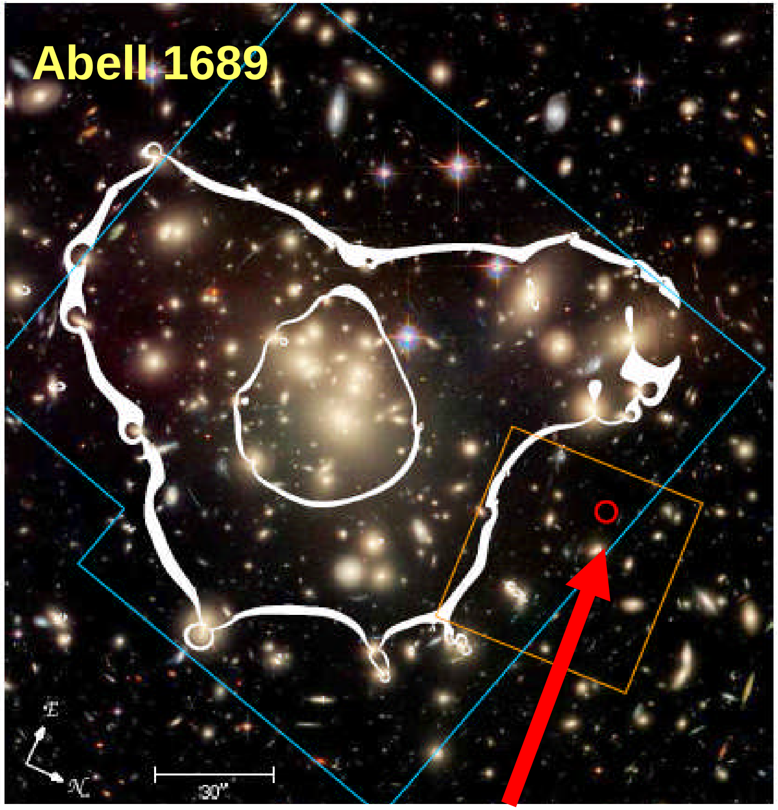
Spitzer → this is already a well-established system 800 Myrs after Big Bang

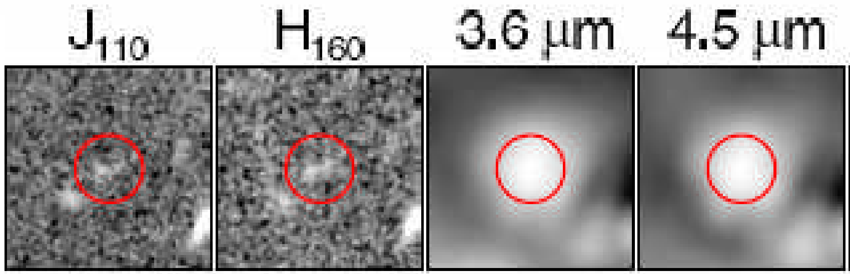
Star formation rate = 2.6 solar masses/yr; stellar mass ~ 0.5% Milky Way

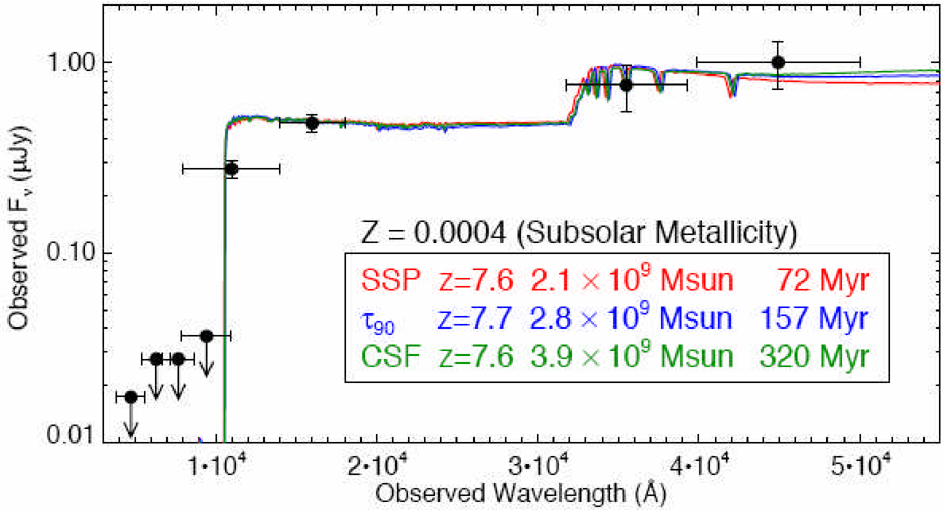
Age at this epoch: 100 – 450 million yrs, so formed at $9 < z_F < 12$

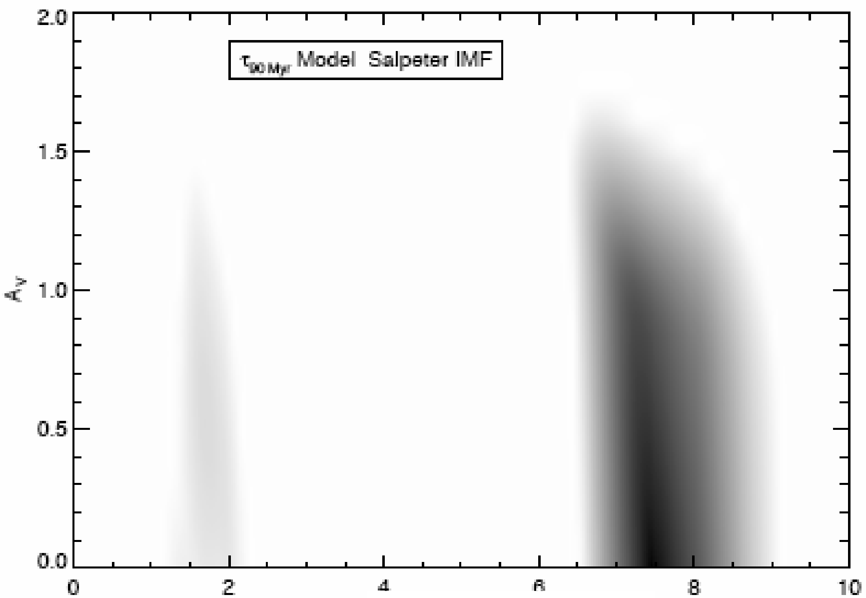
If representative, this is an object in decline after `first light'!

Feb 2008 - a lensed dropout at redshift 7.6!





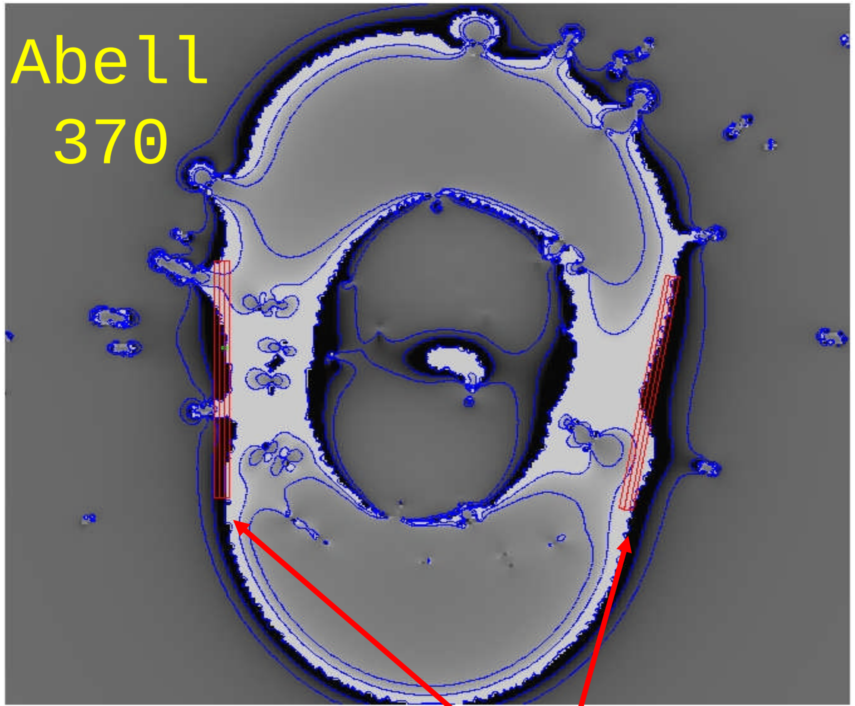




Redshift

Bradley et al (astro-ph/0802.2506)

So Can We See Any Further Back..?



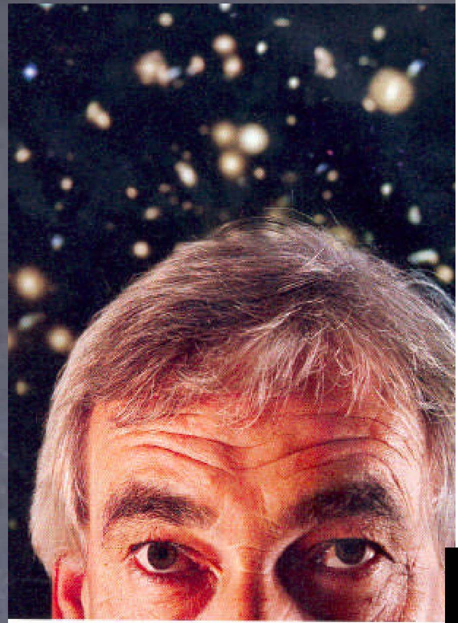
NIRSPEC
Slit
Positions

Critical line mapping of 9 clusters in J-band, corresponding to Lyα at $8.5 < z < 10.4$

Clusters limited to those where the location of the critical line is precisely known from earlier work.

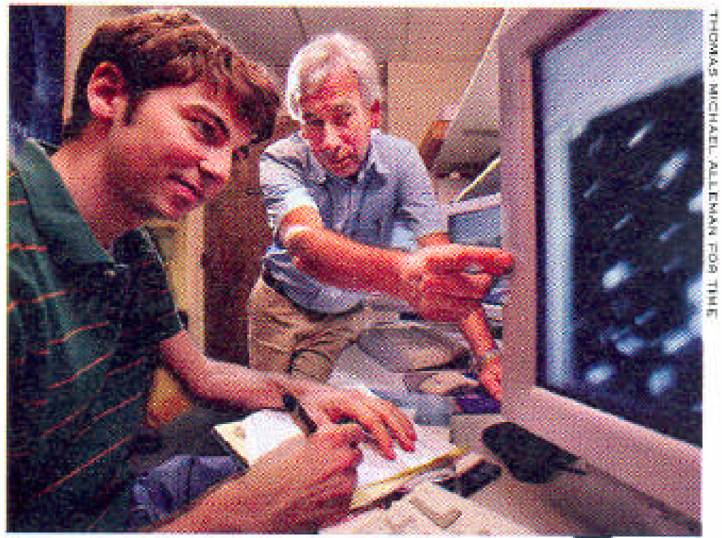
Sensitive to sources magnified by at least ×20 corresponding to intrinsic SFR~0.1 $M_\odot$ yr^{-1}

Stark et al Ap J 663, 10 (2007)



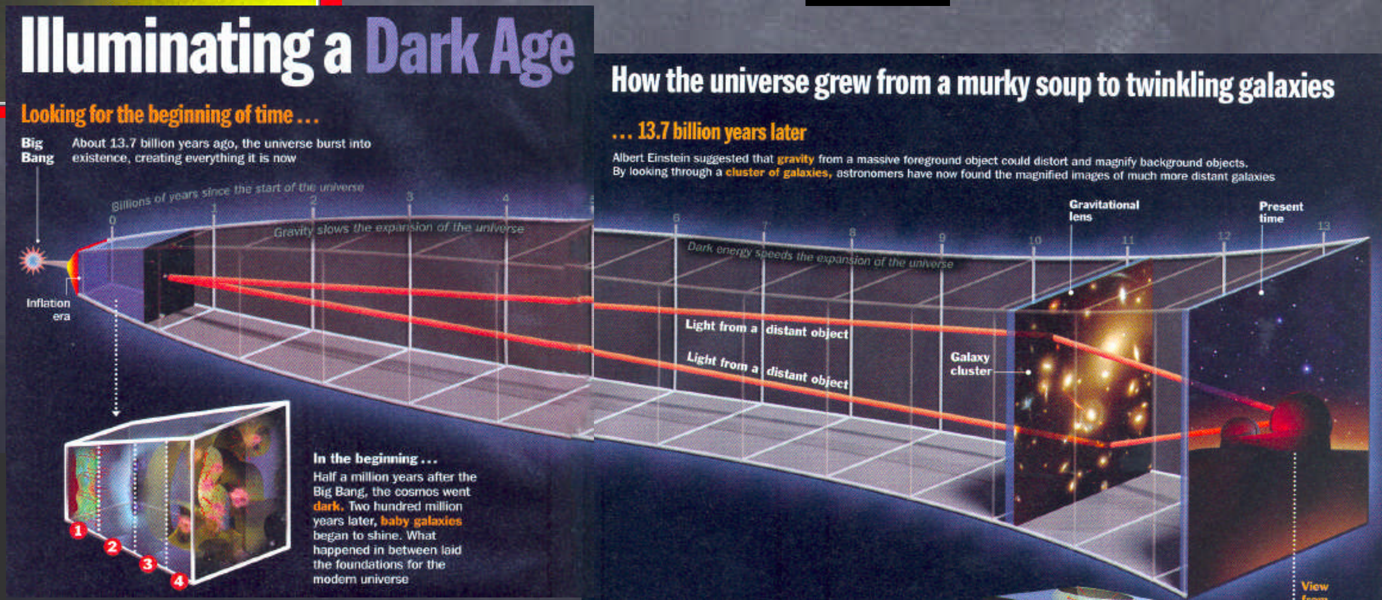
THE GALAXY HUNTER RICHARD ELLIS

With skill and patience he has amassed an extraordinary record of discoveries. His r
takes him within 500 million years of the Big Bang—right to the edge of the Dark A



REMOTE CONTROL

Stark, left, and Ellis, in a Caltech control room, study images beamed from a telescope in Hawaii

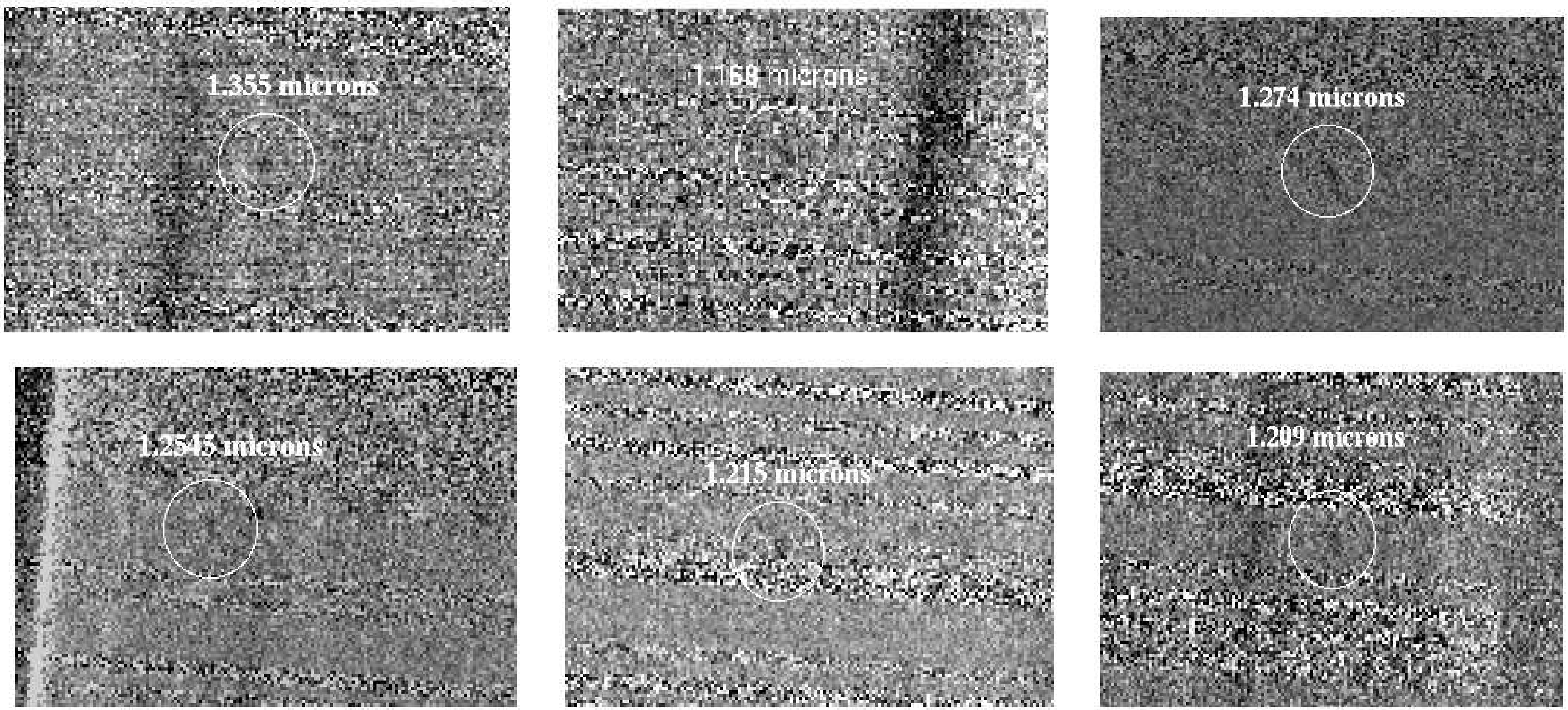


Sep 4 2006

eting,

Candidate Lyα Emitters

8.6 < z < 10.2; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 - 1 $M_{\odot}$ yr^{-1}



Recognize burden of proof that these are z~10 emitters is high

Each detection is > 5σ, seen in independent exposures

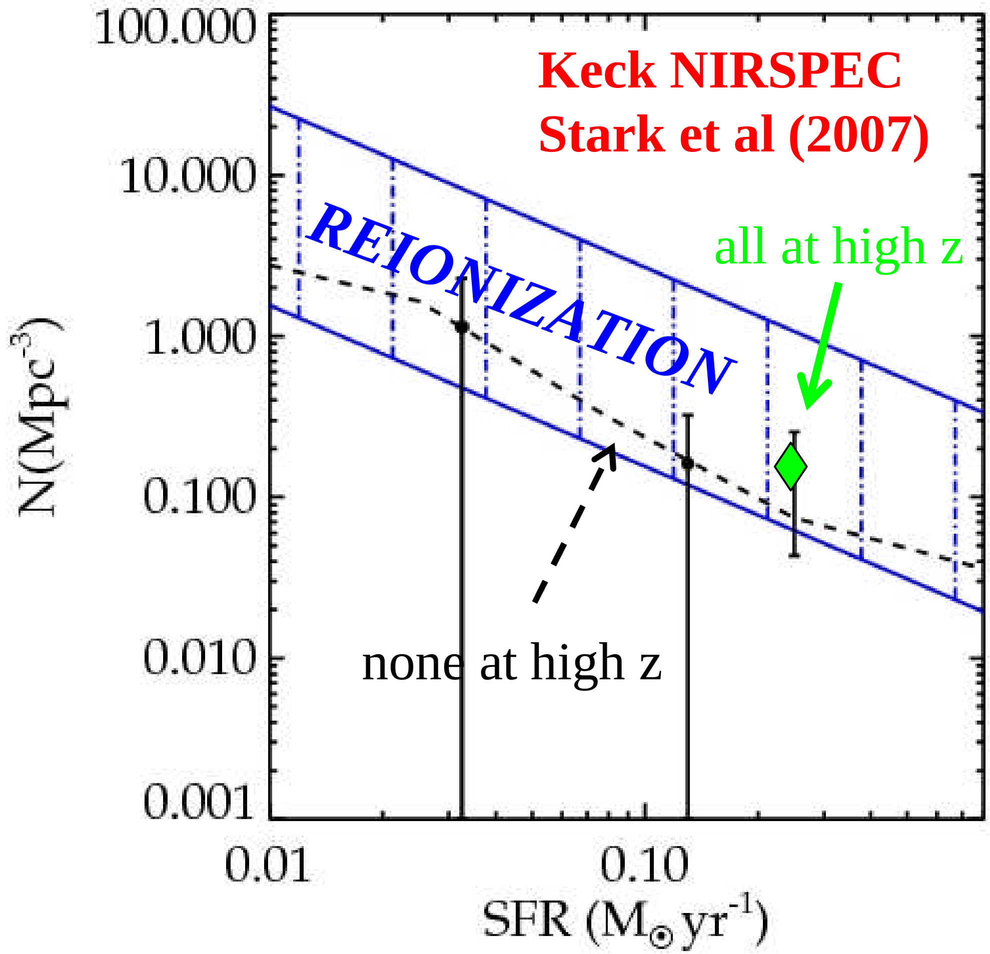
3 sources exceed 5.8σ - expect only 0.005 by chance in data

Did Such Faint Galaxies Cause Reionization?

Can address this by considering the collective UV output of our galaxies per unit area on the sky: are there enough photons to ionize the newly-formed hydrogen in deep space?

If >3 of our 6 candidates are at high z, such low luminosity galaxies may play a dominant role in cosmic reionization: they could even represent the first population

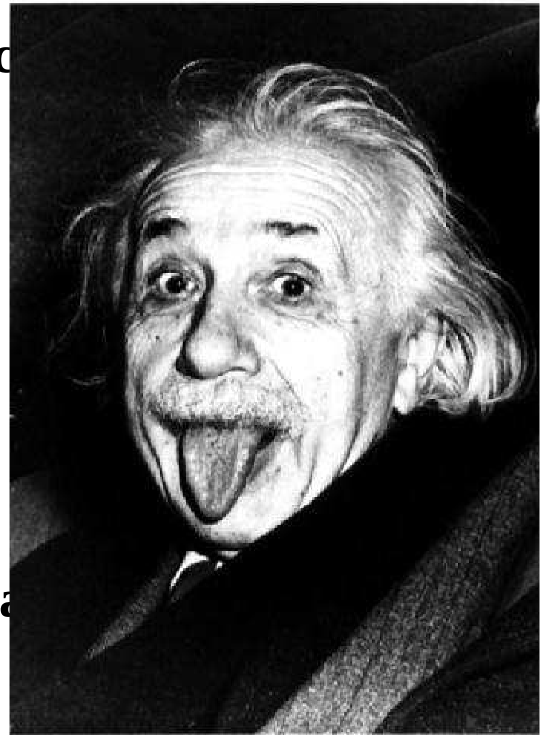
MORE DETAILED STUDIES OF THESE SOURCES THIS YEAR!



Summary

Lensing plays a key role in cosmology!

- **Quantitative measure of DM power spectrum independent of bias associated with baryonic trac**
- **Evolution of DM power spectrum provides valuable measure of equation of state of dark energy: complementing use of distant SNe**
- **Promising future with wide-field imagers for mapping distribution of DM c.f. baryons (JDEM, Euclid)**
- **Strongly-constrained lenses provide important constraints on DM radial profiles on <100 kpc sca testing the possible interactive nature of DM**
- **Strong lenses also offer an unique view of magnified distant sources which ended the "Dark Ages" & reionized the Universe**



[redacted]

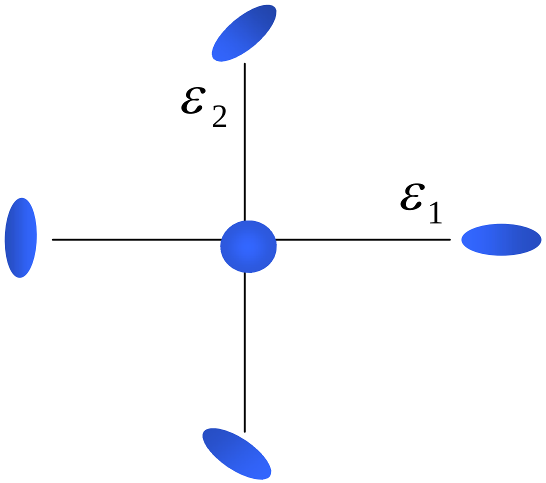
Measuring galaxy shapes

(Kaiser, Squires & Broadhurst 1995)

Galaxies modeled as ellipses determined via quadrupole moments

$$Q_{ij} = \int d^2x \, x_i x_j w(x) I(x)$$

$$\varepsilon_1 = \frac{Q_{11} - Q_{22}}{Q_{11} + Q_{22}}, \quad \varepsilon_2 = \frac{2Q_{12}}{Q_{11} + Q_{22}}$$

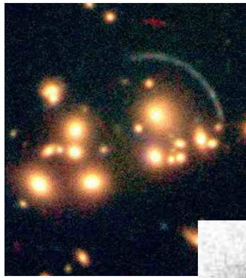


Polarisability P **Shear γ_1, γ_2**

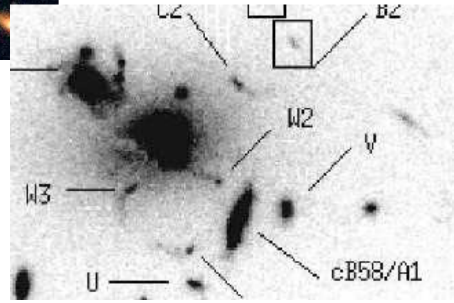
Relation to ellipticity: $\langle \varepsilon_i \rangle = P^{\gamma} \gamma_i$

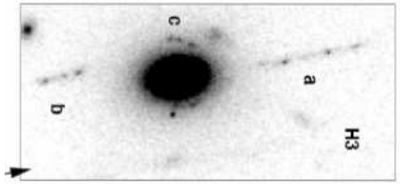
High Redshift Arcs: Record Breakers (1991-2005)

- Cl2244-02 (z=2.237); Mellier et al 1991
- A2218 #384 (z=2.515); Ebbels et al 1996
- MS1512 cB58 (z=2.72); *Yee et al 1996*, Seitz et al 1998
- A2390 (z=4.05); Frye et al 1998, Pellò et al 1999



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.





QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

- MS1358+62 (z=4.92); Franx et al 1997
- A2218 (z=5.7); Ellis et al 2001
- A370 (z=6.56); Hu et al 2002
- ***A2218 (z~6.8); Kneib et al 2005***
- ***A1689 (z~7.6); Bradley et al 2008***

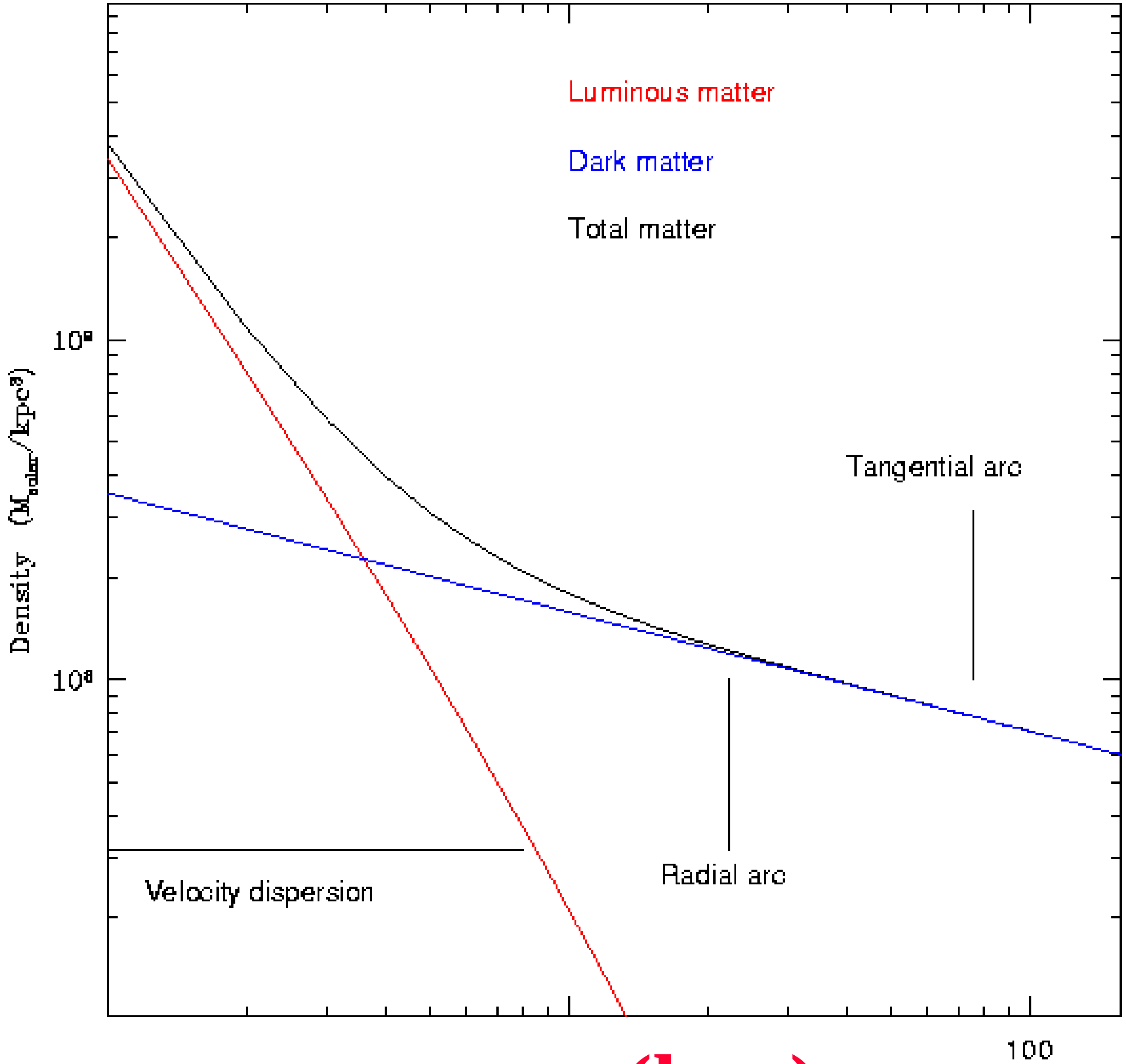
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Spectroscopic verification has always been the challenge!

Best-fitting density profile for MS2137-23

ρ(r)

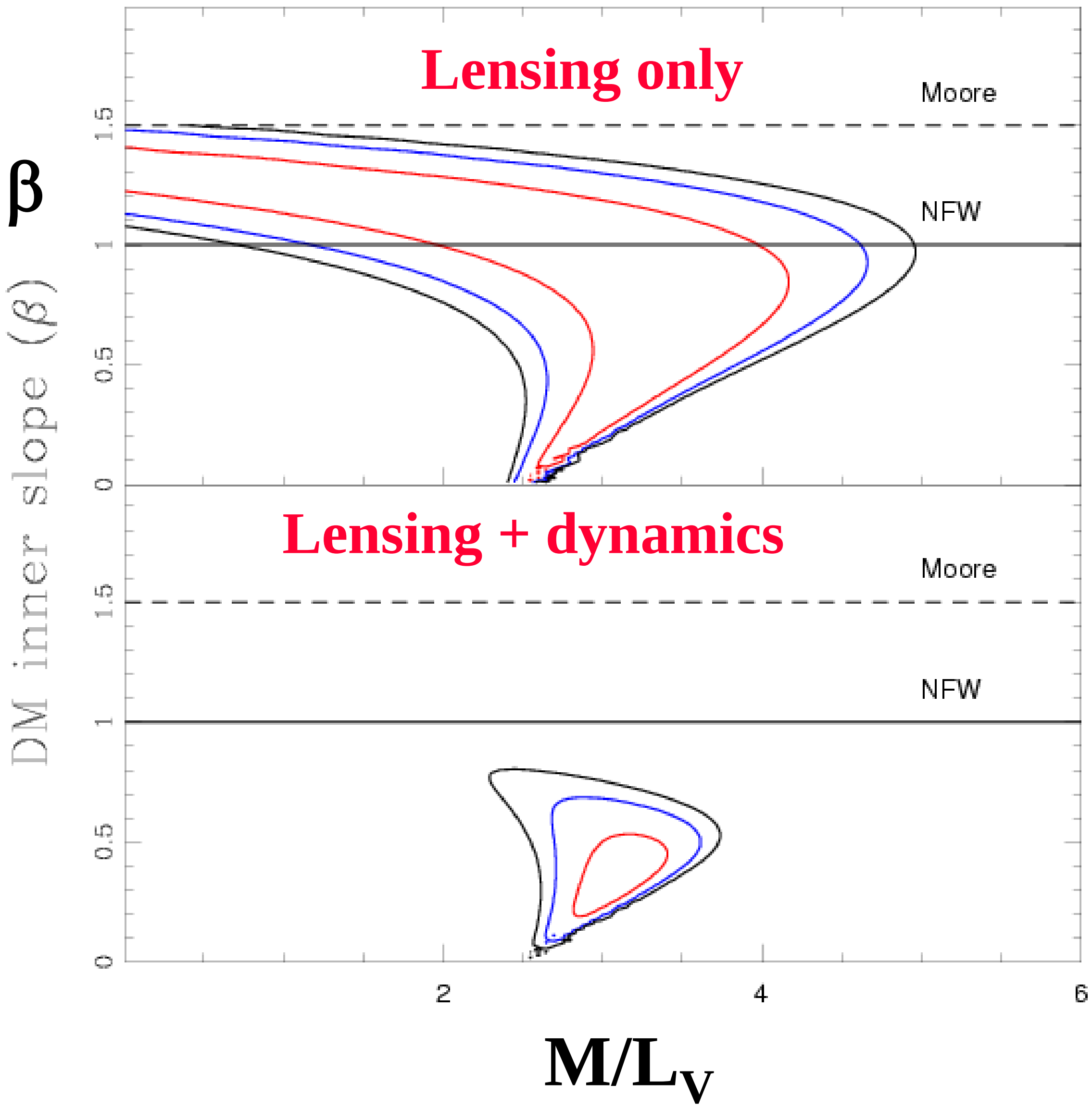


r (kpc)

Likelihood Fit for DM profile

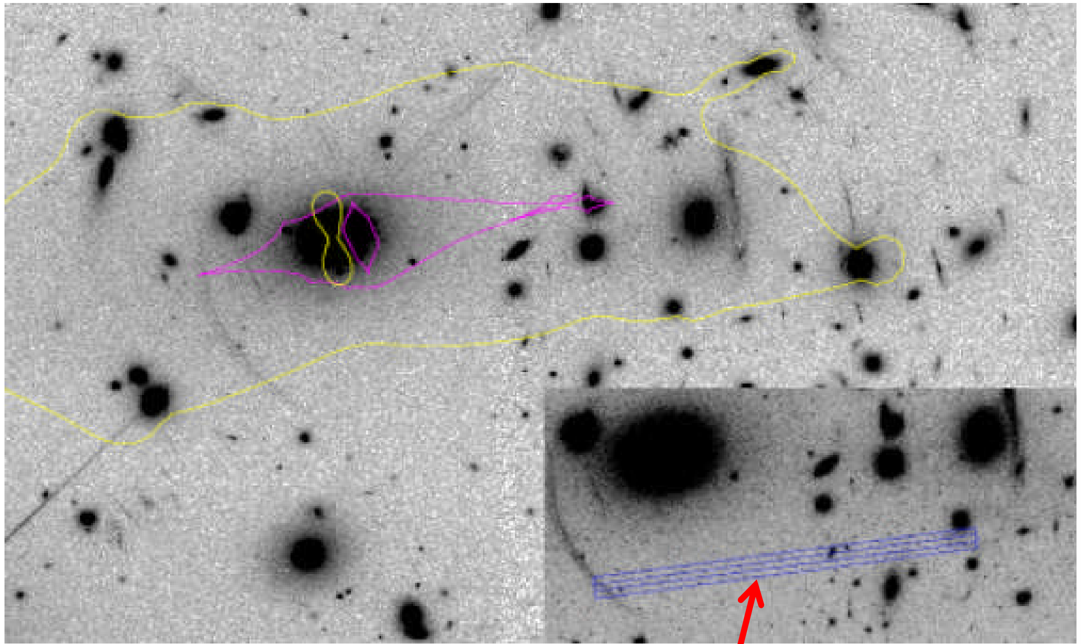
Treating cluster as two-component system (luminous stars + DM), can constrain β over r <75 kpc in terms of M/L of stellar component:

Find flatter slope than indicated in CDM simulations



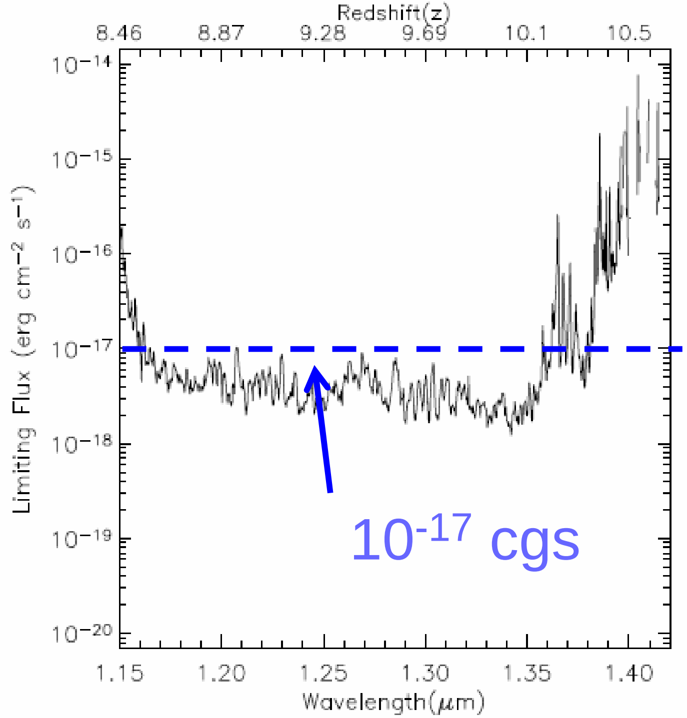
Example: Abell 2390

Cluster critical line for $z_S > 7$



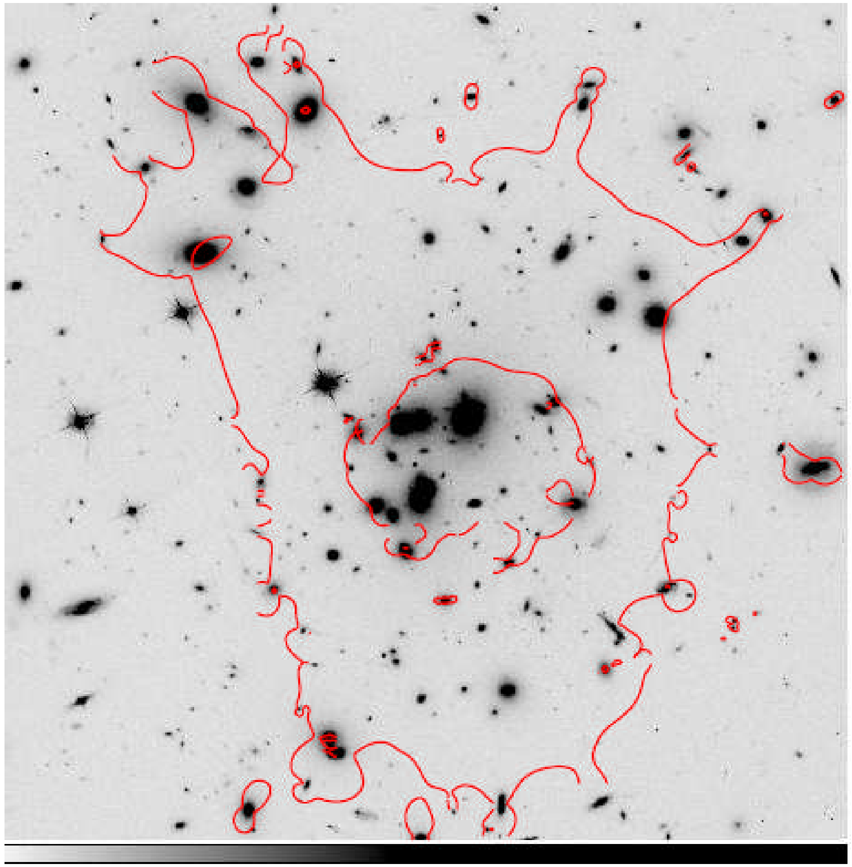
NIRSPEC slit positions

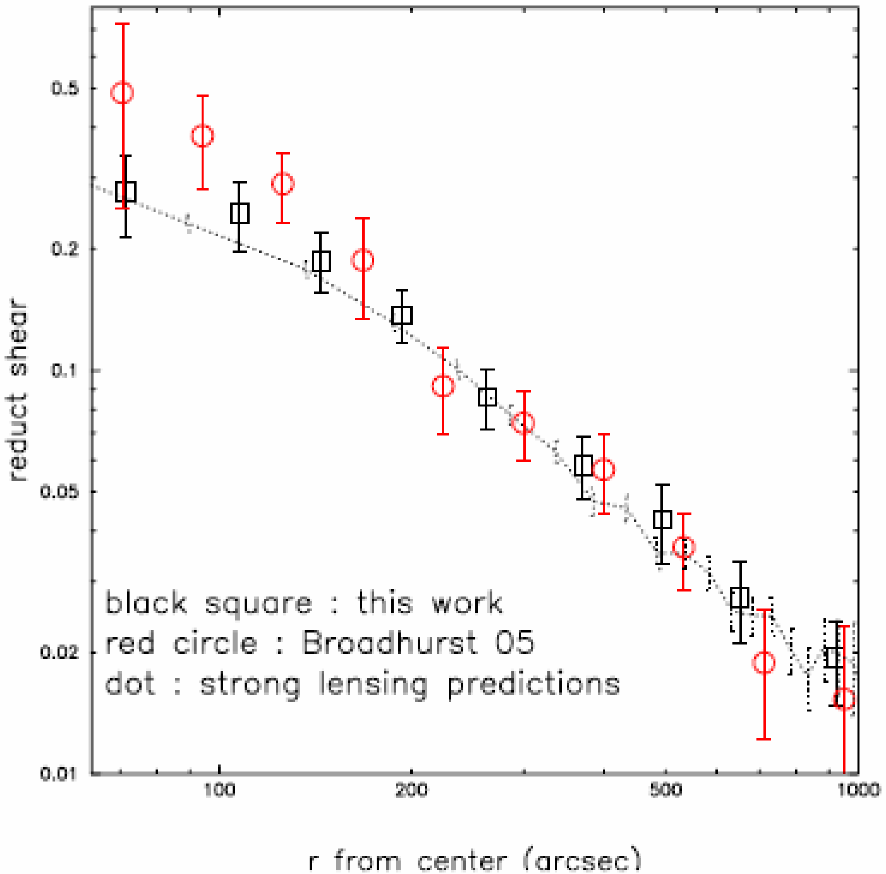
Wavelength sensitivity (1.5hr)



- 9 clusters completed to October 2005
- Clusters have well-defined mass models & deep ACS imaging
- Obs. sensitivity ~ 3-9.10^{-18} cgs; magn. > $\times$15-20 throughout
- Sky area observed: 0.3 arcmin^2; V(comoving)~50 Mpc^3
- 6 promising lensed emitter candidates (>5σ)
- 8.6 < z < 10.1; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 -1 $M_{\odot}$ yr^{-1}

Abell 1689: Possibly the Best Studied Case



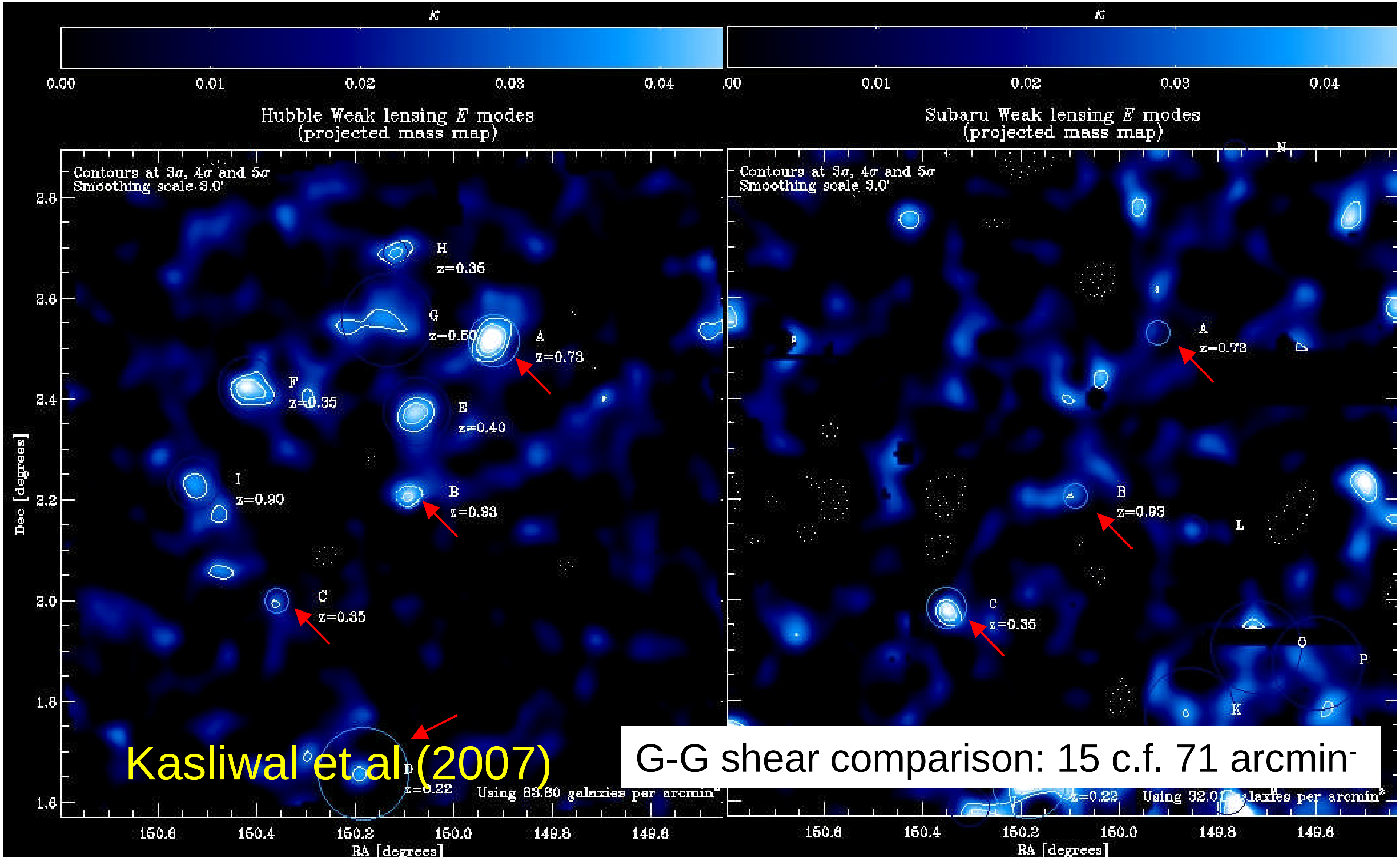


Key issues: strong lensing constraint, foreground subtraction

Limousin et al (2007)

Ground versus Space?

Hubble | **Subaru**



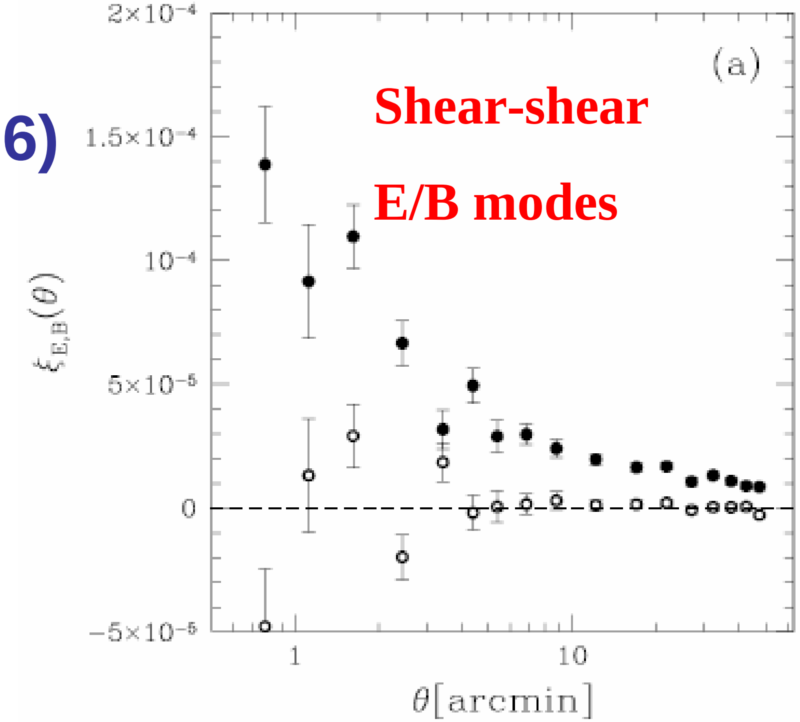
CFHT Wide Field Survey

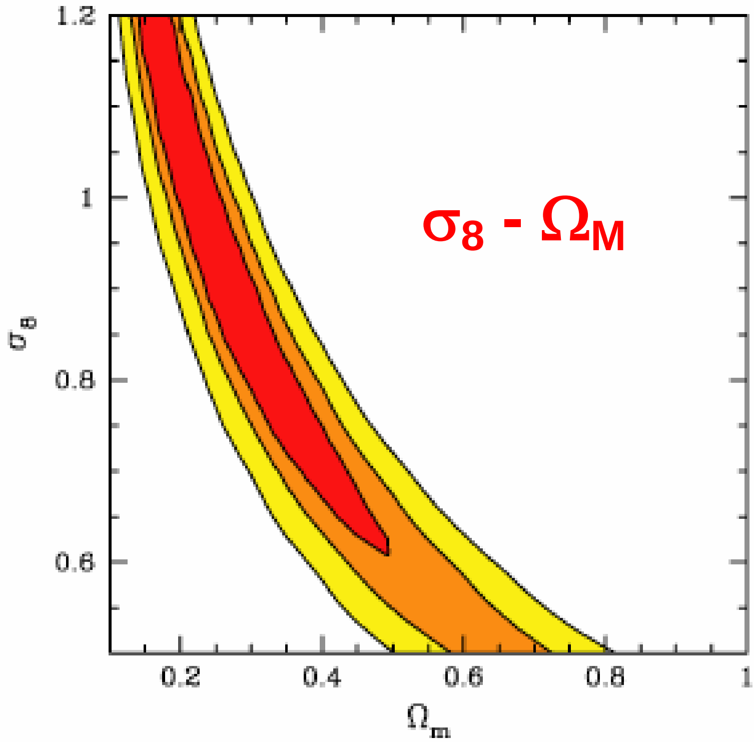
Hoekstra et al Ap J 647, 116 (2006)

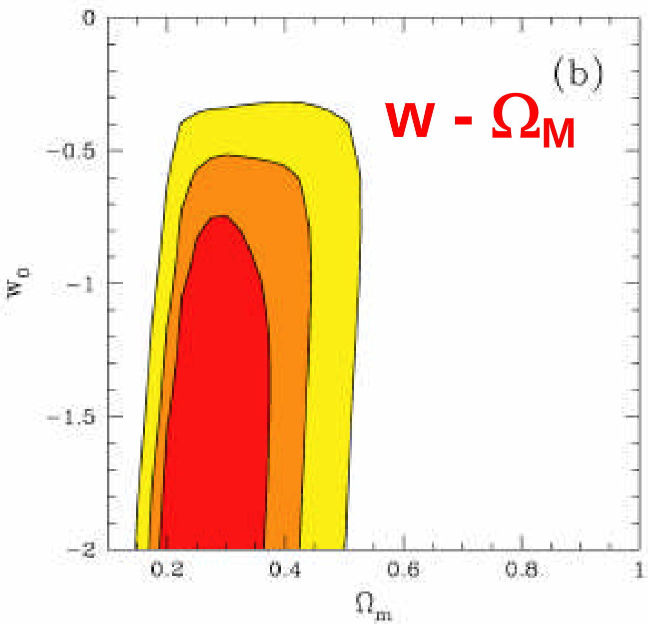
22 deg^2 (from planned 170 deg^2)

Yields $\sigma_8=0.85\pm0.06$ ($\Omega=0.3$)

Fitting P(k) gives w < -0.80 (68%)



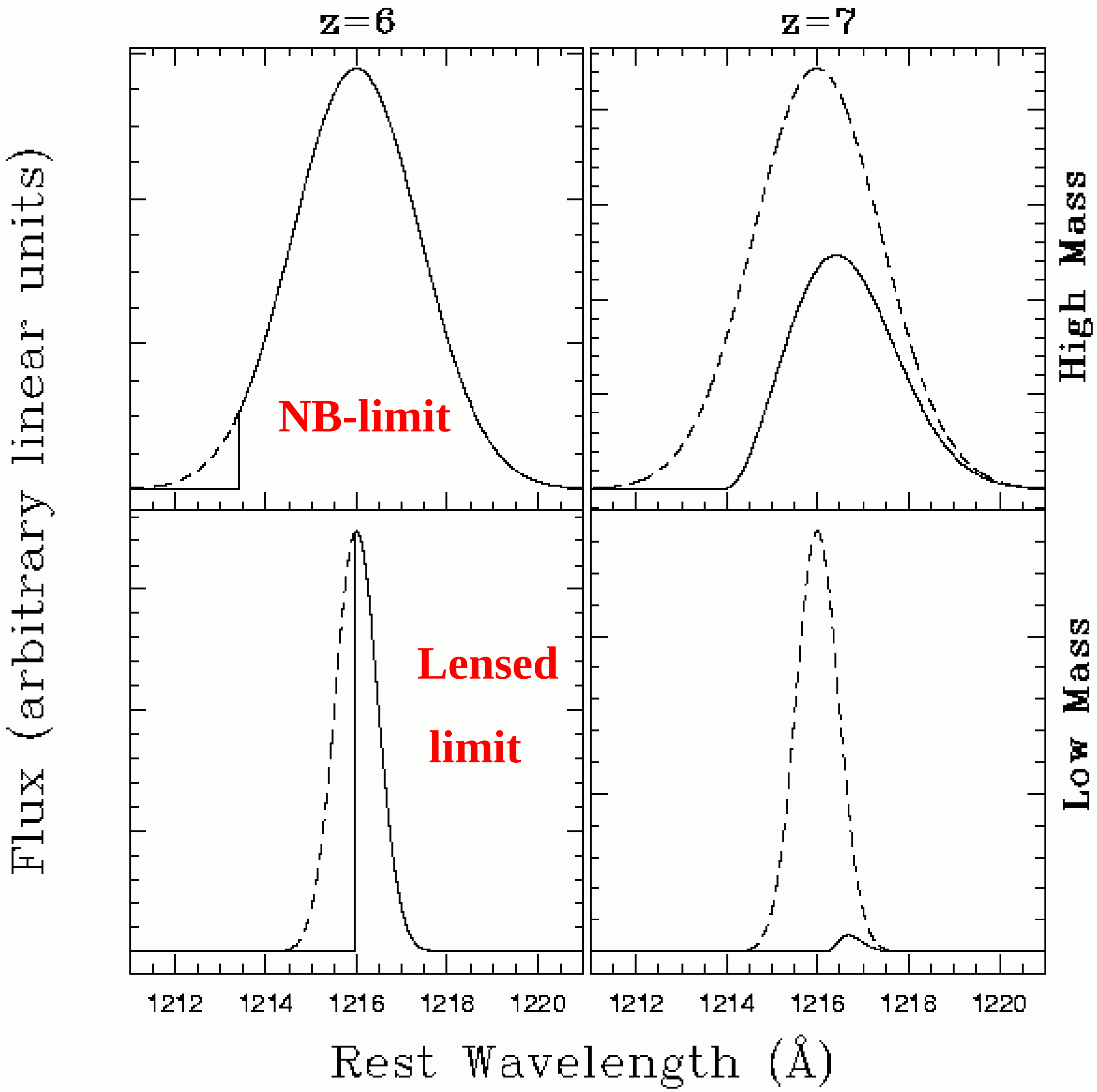




An Indicator of Reionisation?

- **Surface area scanned is only ≈1 arcmin^2 thus such systems are *very abundant* & may represent low mass systems emerging from dark ages**

- **As the Lyα damping wing is more readily absorbed by HI in weaker systems, lensed sources are a more sensitive probe of reionisation**



Implications of Cosmic Acceleration

Why not Λ? two puzzles:

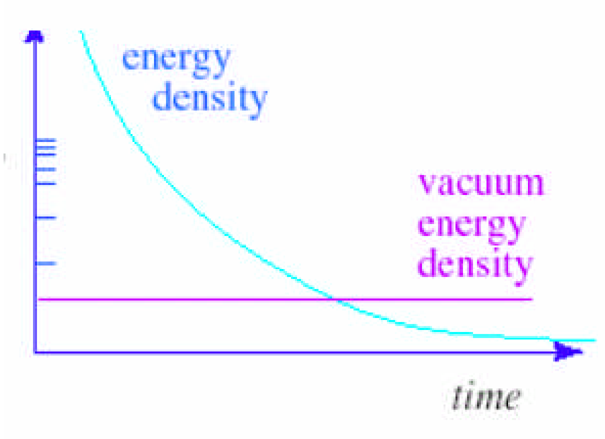
- expect $\Lambda = 8\pi G m_P^4$

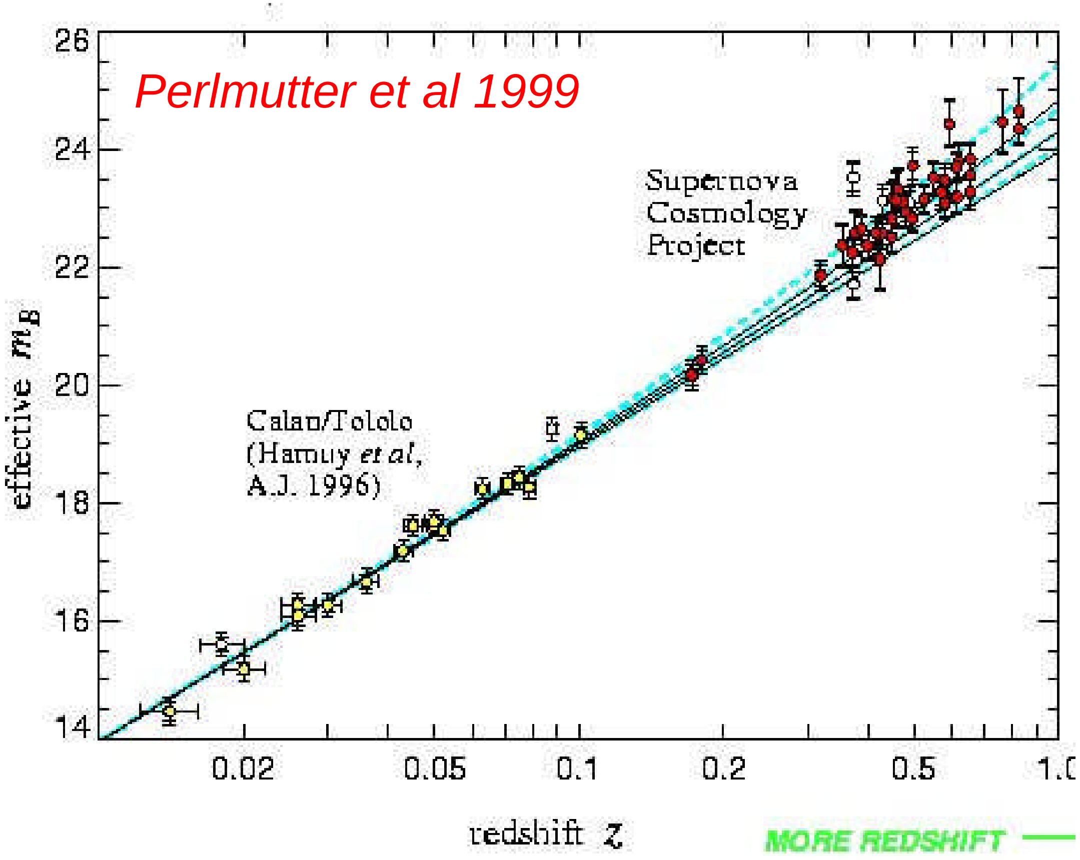
  (10^{120} larger)

- Why acceleration now?

  $\rho_M \propto R^{-3}$ (matter)

  ρ_{vac} = const (vacuum)



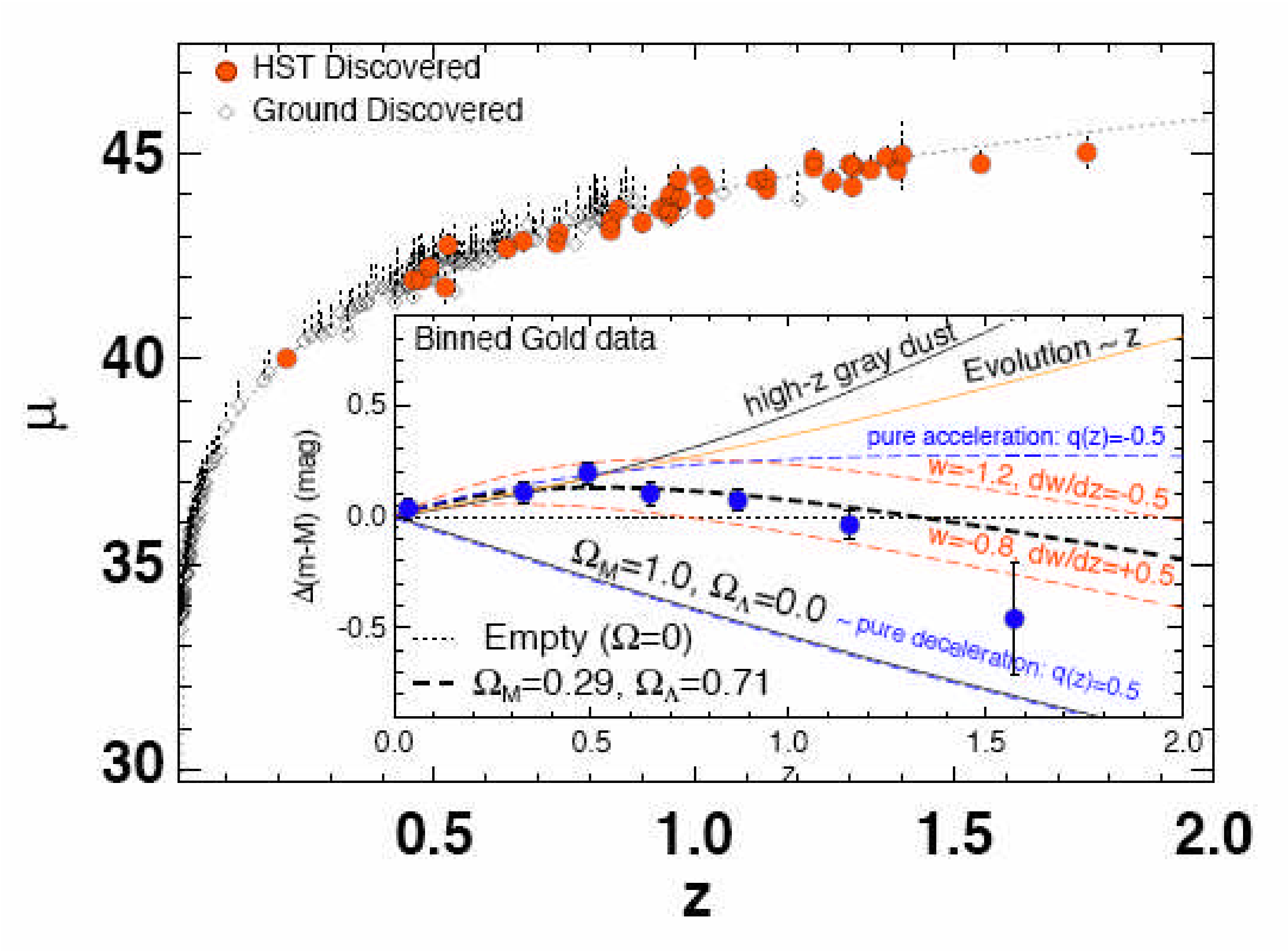


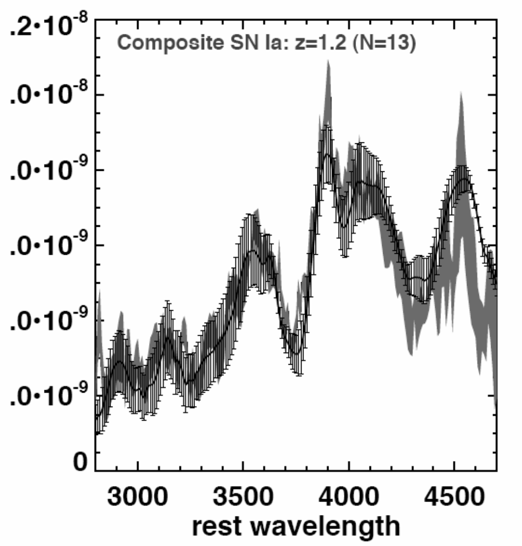
Alternative: new physics - “dark energy”:

quintessence: equation of state $p = w\rho$; $\rho \propto R^{-3(1+w)}$

dynamical scalar field $w = w(t)$

Deep HST Survey





No evolution in Ia spectrum 0<z<1.3

23 HST SNe Ia with z > 1; w < 0 (98% confidence)

Riess et al Ap J 659, 98 (2007)